National Aeronautics and
Space Administration

Cosmic Origins Program Office
Greenbelt, MD 20771

Responses to the Request for Information (RFI)

Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts

NNH12ZDA008L

On May 25, 2012, NASA released a Request for Information (RFI), NNH12ZDA008L, to solicit information pertaining to potential ultraviolet (UV) and visible wavelength astrophysics science investigations. Specifically, NASA sought information that can be used to develop a cohesive set of science goals that motivate and support the development of the next generation of UV/Visible space astrophysics missions and requisite technologies. Information could include broad science goals, justifications for investigation that support COR science goals (cf. http://cor.gsfc.nasa.gov/), specific measurements or proxy observing plans for well-defined astrophysical experiments, or any aspect of scientific inquiry in the UV/Visible that supports the above COR goals.

On August 10, 2012, this solicitation closed, with a total of 34 compliant responses submitted. In this document, we summarize the submissions from the point of view of top-level science performance drivers (such as wavelength range, field of view, or the requirement for temporal sampling) in order to provide a means of quick comparison between responses. This summary is not guaranteed to be comprehensive and is the result of subjective analysis of the responses. Any errors are ours alone, and shall be corrected online to provide the most accurate list possible; consult the RFI web site at http://cor.gsfc.nasa.gov/RFI2012 for this and other information. The entire set of submissions and summary are available in a single 34MB PDF online at http://cor.gsfc.nasa.gov/RFI2012_Responses.

A community workshop will be held at STScI on September 18, 2012 to discuss these responses and to work toward a cohesive set of science drivers for the next NASA UV/Visible mission concept. This workshop can be attended virtually or in person; for more information see http://www.stsci.edu/institute/conference/rfi_copag_2012/.

The process of handling this RFI was accomplished by several people whose contributions we acknowledge here: Mario Perez (COR Program Scientist), John Gagosian (COR Program Executive), Ruth Carter (UV/Visible Study Manager), Beth Keer (COR Deputy Program Manager), Pat Tyler, Aaron McClesky, Michele Smith, and Susan Keddie.

We wish to thank the 222 individual respondents identified in the RFI submissions. It is a testimony to the vibrancy of the field that so many people contributed to this effort.

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Chief Scientist, Cosmic Origins Program
August 29, 2012

Susan G. Neff
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List of RFI Responses:

Title	Last Name
How do molecules and dust form in massive interacting winds?	Gull
The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution	Provencal
The Origin of the Elements Heavier than Iron	Lawler
UVMag: Stellar physics with UV and visible spectropolarimetry	Neiner
Response to Request for Information: NNH12ZDA008L	Ignace
Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems	Carpenter
Understanding Global Galactic Star Formation	Scowen
The Magellanic Clouds Survey - a Bridge to Nearby Galaxies	Scowen
Massive Stars: Key to Solving the Cosmic Puzzle	Wofford
Conditions for Life in the Local Universe	Barstow
The History of Star Formation in Galaxies	Brown
Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies	Goudfrooij
The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies	Williams
A Census of Local Group Ultraviolet Dust Extinction Curves	Gordon
The Baryon Census in a Multiphase Intergalactic Medium	Shull
Quasar Absorption Lines in the Far Ultraviolet: An Untapped Gold Mine for Galaxy Evolution Studies	Tripp
Seeking into the anthropic principle	Gomez de Castro
The escape fraction of ionizing photons from dwarf galaxies	Scarlata
Science from IGM/CGM Emission Mapping	Schiminovich
Project Lyman: Quantifying 11 Gyrs of Metagalactic Ionizing Background Evolution	McCandliss
Synergistic Astrophysics in the Ultraviolet using Active Galactic Nuclei	Kriss
Active Galactic Nuclei and their role in Galaxy Formation and Evolution	Kraemer
UV Spectroscopic Time Domain Studies of Active Galactic Nuclei	Peterson
Extragalactic Lyman-alpha Experiments in the Nearby Universe	Hayes
Galaxy Assembly and SMBH/AGN-growth from Cosmic Dawn to the End of Reionization	Scowen
A UV/Optical/Near-IR Spectroscopic Sky Survey for Understanding Galaxy Evolution	Heap
An Optical and Ultraviolet Cosmological Mapper	Doré
Exoplanet Science of Nearby Stars on a UV/Visible Astrophysics Mission	Noecker
Ultraviolet imaging of exoplanets	Cook
From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy	France
Solar System Science Objectives with the Next UV/Optical Space Observatory	Wong
Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths	Côté
Unique Astrophysics in the Lyman Ultraviolet	Tumlinson
White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)	Ulmer

List of All RFI Respondents:

Ronald J Allen (STScI),
Alessandra Aloisi (STSci),
B-G Andersson (USRA.edu),
Nahum Arav (Virginia Tech),
David R Ardila (Caltech),
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Michael Balogh (U. Waterloo),
Martin A Barstow (U. Leicester),
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Alexander Brown (U. Colorado),
Eric B Burgh (U. Colorado),
Nuria Calvet (U. Michigan),
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Kenneth G Carpenter (NASA/GSFC),
Renyue Cen (Princeton),
Supriya Chakrabarti (U. Massachusetts),
Rupali Chandar (U. Toledo),
Eugene Chiang (U of California, Berkeley),
John T Clarke (Boston Univ),
Geoffrey Clayton (Louisiana State Univ),
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Timothy A Cook (U. Massachusetts),
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Steven R Cranmer (CfA),
Mike Crenshaw (GSU),
Julianne J. Dalcanton (U. Washington),
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Imke de Pater (UC Berkeley),
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Kunio M Sayanagi (Hampton Univ),
Claudia Scarlata (U. Minnesota),
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Joop Schaye (Leiden),
David Schiminovich (Columbia University),
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Bradley Whitmore (STScI),
Benjamin F Williams (U. Washington),
Rogier Windhorst (Arizona State University),
Aida Wofford (STScI),
Michael Wolff (Space Science Inst),
Michael H Wong (Univ. Mich./UC Berkeley),
Stephen Zepf (Michigan State University),

First Name	Last Name	Title	Ang. Res.	Tel. Diam.	λshort	λlong	FOV	Spec. Res.	Sensi-tivity	Phot?	Spec?	Mux?	Time?	Science Category
Theodore	Gull	How do molecules and dust form in massive interacting winds?	<0.010"						<<HST		Y	MOS		Stars
Judith	Provencal	The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution		2m+	912Å	3000Å	10'x10'	50,000	V~35	Y	Y	IFU		Stars
James	Lawler	The Origin of the Elements Heavier than Iron			1900Å	3050Å	10'x10'	60,000			Y	MOS		Stars
Coralie	Neiner	UVMag: Stellar physics with UV and visible spectropolarimetry			1170Å	0.87μm		25,000	V~10	Y; pol			Y	Stars
Richard	Ignace	Response to Request for Information: NNH12ZDA008L								Y; pol			Y	Stars
Kenneth	Carpenter	Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems	<0.0001"							Y	Y		Y	Stars
Paul	Scowen	Understanding Global Galactic Star Formation	0.020"	1.5m-4m	2500Å	0.95μm	15'x15'			Y				Star Formation
Paul	Scowen	The Magellanic Clouds Survey - a Bridge to Nearby Galaxies	<0.1"	2m-4m	2000Å	~1μm	10'x10'	30,000	10^{-16} erg/s/cm^2	Y	Y			Star Formation; Stars
Aida	Wofford	Massive Stars: Key to Solving the Cosmic Puzzle		≥10m	912Å	0.9μm		6,000			Y			Nearby Galaxies; Stars
Martin	Barstow	Conditions for Life in the Local Universe			1000Å	3000Å		100,000		Y	Y			Nearby Galaxies; Stars
Thomas	Brown	The History of Star Formation in Galaxies		8-16m					V~35	Y				Nearby Galaxies
Paul	Goudfrooij	Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies		2m/8m			20'x20'			Y	Y	MOS		Nearby Galaxies
Benjamin	Williams	The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies	4xHST	8m-10m			100xHST			Y				Nearby Galaxies
Karl	Gordon	A Census of Local Group Ultraviolet Dust Extinction Curves	0.1"		1150Å	4100Å		1000		Y	Y			Nearby Galaxies
Michael	Shull	The Baryon Census in a Multiphase Intergalactic Medium		>4m	<1000Å			~100,000	2mÅ EW		Y			IGM
Todd	Tripp	Quasar Absorption Lines in the Far Ultraviolet: An Untapped Gold Mine for Galaxy Evolution Studies			1000Å			like COS	<<HST		Y			IGM
Ana	Gomez de Castro	Seeking into the anthropic principle			1000Å	4000Å								IGM
Claudia	Scarlata	The escape fraction of ionizing photons from dwarf galaxies	1"		2000Å	0.63μm		5000	~32nd AB	Y	Y			IGM
David	Schiminovich	Science from IGM/CGM Emission Mapping			1250Å	4000Å	4'x4'	5000	5 γ/cm^2/s/s		Y	MOS		IGM
Stephan	McCandliss	Project Lyman: Quantifying 11 Gyrs of Metagalactic Ionizing Background Evolution			1000Å	4000Å	0.5°^{2}		10^{-4} FEFU		Y	MOS		IGM
Gerard	Kriss	Synergistic Astrophysics in the Ultraviolet using Active Galactic Nuclei		8m	900Å	3200Å		15,000	10 FEFU		Y		Y	AGN; IGM
Steven	Kraemer	Active Galactic Nuclei and their role in Galaxy Formation and Evolution	<0.0001"					~500		Y	Y			AGN
Bradley	Peterson	UV Spectroscopic Time Domain Studies of Active Galactic Nuclei			1100Å	3000Å		600			Y		Y	AGN
Matthew	Hayes	Extragalactic Lyman-alpha Experiments in the Nearby Universe			1216Å	3500Å	0.1°^{2}	100	10^{-16} erg/s/cm^2		Y	Any		Galaxy Evolution
Paul	Scowen	Galaxy Assembly and SMBH/AGN-growth from Cosmic Dawn to the End of Reionization	≤0.040"	2.4m-4m	1216Å	~1μm	15'x15'		~30th AB	Y	Y	Slitless		Galaxy Evolution
Sara	Heap	A UV/Optical/Near-IR Spectroscopic Sky Survey for Understanding Galaxy Evolution		0.5m-2.4m	2000Å	1.7μm			0.001 FEFU		Y			Galaxy Evolution
Olivier	Doré	An Optical and Ultraviolet Cosmological Mapper	30"	0.5m	1216Å	0.85μm			10^{-16} erg/s/cm^2	Y	Y			Galaxy Evolution
Charlie	Noecker	Exoplanet Science of Nearby Stars on a UV/Visible Astrophysics Mission		2m-4m	UV	NIR		100		Y; coron.	Y		Y	Planets
Timothy	Cook	Ultraviolet imaging of exoplanets		0.5m-1.5m						Y; coron.	Y			Planets
Kevin	France	From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy			912Å	4000Å	10'x10'	100,000	0.01 FEFU		Y	MOS		Planets
Michael	Wong	Solar System Science Objectives with the Next UV/Optical Space Observatory	0.05"		UV	IR		2500		Y	Y		Y	Solar System
Patrick	Côté	Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths	0.15"	1m			0.67°^{2}		NUV~26	Y			Y	Multiple
Jason	Tumlinson	Unique Astrophysics in the Lyman Ultraviolet			912Å	1216Å		50,000	~30th AB		Y	MOS or IFU		Multiple
Melville	Ulmer	White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)		2.4m	UV	Vis	6'x6'		~10X HST	Y	Y			Multiple

RFI Responses:

1. Theodore Gull, "How do molecules and dust form in massive interacting winds?"

How do molecules and dust form in massive interacting winds? One of the mysteries of interstellar dust is how it forms. While prodigious amounts of dust are seen in the interstellar medium, most models assume a dust core and then proceed to build a mantle of condensed molecules around this core. This science objective tries to understand how molecules and dust cores form in massive winds. At high redshifts, evidence is that metal enrichment and dust occurred early after the first stars formed. We simply do not understand how the dust cores form in stellar atmospheres, enriched by carbon and oxygen the basic building blocks for many molecules. Yet molecular and dust formation is so robust that both form even in stars with greatly depleted amounts of carbon and oxygen, as exemplified by Eta Carinae. Massive stars, that evolved rapidly, must play a dominant role in chemical enrichment early in the Universe. By studying current day systems, we can gain insight on the earliest mixing in young galaxies.

2. Judith Provencal, "The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution"

White dwarfs are rich forensic laboratories that provide links between the history and future evolution of the Milky Way Galaxy. The structure and composition of white dwarfs contain the records of the final stages of stellar evolution. As a newly forming white dwarf evolves through the planetary nebula phase, large quantities of processed material are injected into the interstellar medium. The chemical evolution of the Galaxy is traced through subsequent generations of stars formed from this contaminated material. The distribution of Milky Way white dwarfs in temperature constrains models of galactic and cosmological evolutionary history. Type I supernovae, in which an accreting white dwarf undergoes a thermonuclear event, are used as distance indicators demonstrating the acceleration of the universe. Underlying all these studies is the theoretical mass-radius relation for electron degenerate matter, an important consequence of which is the existence of an upper mass limit for white dwarf stars. The ultraviolet waveband is particularly important for the study of these objects. A significant fraction of white dwarf emergent flux appears in the UV, especially for the hotter stars. In addition, traces of elements heavier than hydrogen or helium are, in general, only detected in this waveband or at shorter wavelengths that are also only accessible from space. We broadly outline the importance of:

1) the white dwarf mass-radius relation
2) the white dwarf luminosity function
3) white dwarf spectroscopy

in understanding important cosmological questions, including questions of stellar physics in extreme conditions, galactic evolution, stellar formation and evolution, and the chemical distribution of material in our galaxy."

3. James Lawler, "The Origin of the Elements Heavier than Iron"

> Understanding the origin of the elements is one of the major challenges of modern astrophysics. This goal is expressed in several of the Cosmic Origins science questions, including how the first stars influenced their environments, how the chemical elements were dispersed through the circumgalactic medium, how galaxies and their constituent stars formed and evolved, and how baryons destined to form planets grow to heavy atoms.

4. Coralie Neiner, "UVMag: Stellar physics with UV and visible spectropolarimetry"

> We propose to study the formation, structure, evolution and environment of all types of stars in particular through the measurement of their magnetospheres, i.e. through the association of spectropolarimetry and spectroscopy in the UV and visible domains.

5. Richard Ignace, "Time Series and Polarimetric Studies of Structure in Stellar winds and Outflows: Response to Request for Information: NNH12ZDA008L"

> This response to the RFI will emphasize the importance of times series studies and polarimetric capability for future NASA missions. The issue of "structure" in winds and disks has become of central importance of late. The clumping aspects of stellar winds has proven to be critical for obtaining better mass loss rates of massive stars, with consequences for understanding both stellar and galactic evolution. Magnetism of massive stars has matured greatly as a subfield. Detections are now regularly reported, and there have been significant successes from theory in explaining a number of phenomena associated with rotating magnetospheres and stellar winds (although it is clear that there is much work remaining). Although the ability to obtain spectral energy distributions or high quality line profiles are and will continue to be important, another "style" of observing that has proven to be of immense scientific value and highly productive has been time series studies.

6. Kenneth Carpenter, "Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems"

> Understanding the formation, structure, and evolution of stars and stellar systems remains one of the most basic pursuits of astronomical science, and is a prerequisite to obtaining an understanding of the Universe as a whole. The evolution of structure and transport of matter within, from, and between stars are controlled by dynamic processes, such as variable magnetic fields, accretion, convection, shocks, pulsations, and winds. Future long-baseline (0.5-1.0 km) observatories (i.e., space-based interferometers and sparse aperture telescopes) will achieve resolutions of 0.1 milli-arcsec (mas), a gain in spatial resolution comparable to the leap from Galileo to HST. As a result, spectral imaging observations from such facilities will enable a quantum leap in our understanding of stars and stellar systems. In this whitepaper, we discuss the compelling new scientific opportunities for understanding the formation, structure, and evolution of stars and stellar systems that can be enabled by dramatic increases in UV-Optical angular resolution to the sub-mas level. An Ultraviolet-Optical Interferometer (UVOI) with apertures on that order would provide direct spectral imaging of spatial structures and dynamical processes in the various stages of stellar evolution for a broad range of stellar types.

7. Paul Scowen, "Understanding Global Galactic Star Formation"

> We propose to the community a comprehensive UV/optical/NIR imaging survey of Galactic star formation regions to probe all aspects of the star formation process, a listed key question in the Cosmic Origins science goals: what are the mechanisms by which stars and their planetary systems form? The primary goal of such a study is to understand the evolution of circumstellar protoplanetary disks and other detailed aspects of star formation in a wide variety of different environments. This goal requires a comprehensive emission-line survey of nearby star-forming regions in the Milky Way, where a high spatial resolution telescope+camera will be capable of resolving circumstellar material and shock structures. In addition to resolving circumstellar disks themselves, such observations will study shocks in the jets and outflows from young stars, which are probes of accretion in the youngest protoplanetary disks still embedded in their surrounding molecular clouds. These data will allow the measurement of proper motions for a large sample of stars and jets/shocks in massive star-forming regions for the first time, opening a new window to study the dynamics of these environments. It will require better than 30 mas resolution and a stable PSF to conduct precision astrometry and photometry of stars and nebulae. Such data will allow production of precise color-color and color-magnitude diagrams for millions of young stars to study their evolutionary states, while also providing stellar rotation, multiplicity, and clustering statistics as functions of environment and location in the Galaxy. For the first time, one would be able to systematically map the detailed excitation structure of HII regions, stellar winds, supernova remnants, and supershells/superbubbles. This survey will provide the basic data required to understand star formation as a fundamental astrophysical process that controls the evolution of the baryonic contents of the Universe

8. Paul Scowen, "The Magellanic Clouds Survey - a Bridge to Nearby Galaxies"

To address several key Cosmic Origins program science questions, such as 1) "How are chemical elements distributed in galaxies and dispersed into the circumgalactic and intergalactic medium" and 2) "how does baryonic matter flow from the intergalactic medium to galaxies and ultimately into planets", we outline to the community the value of a three-phase Magellanic Clouds Survey. This survey consists of three components: I) a complete-area, high resolution, multi-band UV-near-IR broadband survey; II) a narrowband survey in 7 key nebular filters to cover a statistically significant sample of representative HII regions and a large-area, contiguous survey of the diffuse, warm ISM; and III) a comprehensive FUV spectroscopic survey of 1300 early-type stars. The science areas enabled by such a dataset are as follows: A) assessment of massive star feedback in both HII regions and the diffuse, warm ISM; B) completion of a comprehensive study of the 30 Doradus giant extragalactic HII region (GEHR); C) development and quantitative parameterization of stellar clustering properties; D) extensive FUV studies of early-type stellar atmospheres and their energy distributions; and E) similarly extensive FUV absorption-line studies of molecular cloud structure and ISM extinction properties.

9. Aida Wofford, "Massive Stars: Key To Solving The Cosmic Puzzle"

We describe observations in the nearby universe (<100 Mpc) with a ≥10-m spacebased telescope having imaging and spectral capabilities in the range 912-9000 Å that would enable advances in the fields of massive stars, young populations, and star-forming galaxies, that are essential for achieving the Cosmic Origins Program objectives i) how are the chemical elements distributed in galaxies and dispersed in the circumgalactic and intergalactic medium; and ii) when did the first stars in the universe form, and how did they influence their environments. We stress the importance of observing hundreds of massive stars and their descendants individually, which will make it possible to separate the many competing factors that influence the observed properties of these systems (mass, composition, convection, mass-loss, rotation rate, binarity, magnetic fields, and cluster mass).

10. Martin Barstow, "Conditions for Life in the Local Universe"

This response to the RFI addresses the "local" aspect of the cosmic feedback and flow of baryons to support life, assuming that other elements will be considered in complementary submissions.

11. Thomas Brown, "The History of Star Formation in Galaxies"

> If we are to develop a comprehensive and predictive theory of galaxy formation and evolution, it is essential that we obtain an accurate assessment of how and when galaxies assemble their stellar populations, and how this assembly varies with environment. There is strong observational support for the hierarchical assembly of galaxies, but our insight into this assembly comes from sifting through the resolved field populations of the surviving galaxies we see today, in order to reconstruct their star formation histories, chemical evolution, and kinematics. To obtain the detailed distribution of stellar ages and metallicities over the entire life of a galaxy, one needs multi-band photometry reaching solar-luminosity main sequence stars. The Hubble Space Telescope can obtain such data in the low-density regions of Local Group galaxies. To perform these essential studies for a fair sample of the Local Universe, we will require observational capabilities that allow us to extend the study of resolved stellar populations to much larger galaxy samples that span the full range of galaxy morphologies, while also enabling the study of the more crowded regions of relatively nearby galaxies. With such capabilities in hand, we will reveal the detailed history of star formation and chemical evolution in the universe.

12. Paul Goudfrooij, "Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies"

> Star formation plays a central role in the evolution of galaxies and of the Universe as a whole. Studies of star-forming regions in the local universe have shown that star formation typically occurs in a clustered fashion. Building a coherent picture of how star clusters form and evolve is therefore critical to our overall understanding of the star formation process. Most clusters disrupt after they form, thus contributing to the field star population. However, the most massive and dense clusters remain bound and survive for a Hubble time. These globular clusters provide unique observational probes of the formation history of their host galaxies. In particular, the age and metallicity can be determined for each globular cluster individually, allowing the distribution of ages and metallicities within host galaxies to be constrained. We show how space-based UV-to-Near-IR imaging covering a wide field of view ($\gtrsim 20'$ per axis) and deep UV/Optical multi-object spectroscopy of globular cluster systems in nearby galaxies would allow one to place important new constraints on the formation history of early-type galaxies and their structural subcomponents (e.g., bulge, halo).

13. Benjamin Williams, "The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies"

> Models of galaxy formation and evolution are only as reliable as our knowledge of the individual stars responsible for the light we detect. From the prescriptions for stellar feedback, to numerical simulations, to the interpretation of galaxy colors and spectra, galaxy evolution research depends at its core on reliable star formation and evolution models. These models are calibrated using observations of resolved stellar populations in a wide range of environments. Studies of stellar populations in the UV have made great strides in the past decade with the GALEX UV surveys and the UV-sensitive WFC3 camera on HST. With the phenomenal data that these instruments have provided, we have learned surprising UV properties of the stellar populations of galaxies and star clusters. While these observations have certainly shed light on the evolution of stars and star clusters, the picture is still far from complete. To fully understand the processes that shape star formation of clusters and OB associations in galaxies with a range of masses, metallicities, and gas content will require the next generation of UV telescopes and instrumentation. To make significant progress, goals for this future instrumentation will need to include improved spatial resolution to resolve individual stars in crowded extragalactic environments and a larger field of view to cover nearby galaxies with fewer pointings. Future observations will then be able to produce the required libraries of resolved stars in carefully selected UV bands to reveal the physical properties of the stars and properly making the necessary observations.

14. Karl Gordon, "A Census of Local Group Ultraviolet Dust Extinction Curves"

> Interstellar dust plays a central role in shaping the detailed structure of the interstellar medium, thus strongly influencing star formation and galaxy evolution. Ultraviolet extinction curves provide one of the main pillars of our understanding of interstellar dust while also being one of the limiting factors when interpreting observations of distant galaxies. Our observational picture of extinction curves is strongly biased to nearby regions in the Milky Way. However, the few extinction curves measured in the Magellanic Clouds show curves that are quite different from those seen in the Milky Way. We propose an observational program to obtain a census of ultraviolet dust extinction curves in the Local Group by measuring large, statistically significant samples of extinction curves in each Local Group galaxy. This program requires sensitive medium-band UV and blue-optical imaging and followup R~1000 spectroscopy of 1000's of sources. This census will, for the first time, provide a full census of dust and its variation with environment and galaxy type. It would simultaneously generate one of the largest ultraviolet spectral libraries ideal for a range of hot star studies. Such a census will revolutionize our understanding of the dependence of dust properties on local environment providing both an empirical description as well as strong constraints on dust grain and evolution models.

15. Michael Shull, "The Baryon Census in a Multiphase Intergalactic Medium"

In this white paper, we summarize the current observations of the baryon census at low redshift (Shull, Smith, & Danforth 2012). We then suggest improvements in measuring the baryons in major components of the IGM and CGM with future UV and X-ray spectroscopic missions that could find and map the missing baryons, the fuel for the formation and chemical evolution of galaxies.

16. Todd Tripp, "Quasar Absorption Lines in the Far Ultraviolet: An Untapped Gold Mine for Galaxy Evolution Studies"

Most of the baryons are exceedingly difficulty to observe, at all epochs. Theoretically, we expect that the majority of the baryonic matter is located in low-density, highly ionized gaseous envelopes of galaxies – the "circumgalactic medium" – and in the highly ionized intergalactic medium. Interactions with the CGM and IGM are thought to play crucial roles in galaxy evolution through accretion, which provides the necessary fuel to sustain on-going star formation, and through feedback-driven outflows and dynamical gas-stripping processes, which truncate and regulate star formation as required in various contexts (e.g., low- mass vs. high-mass galaxies; cluster vs. field). Due to the low density and highly ionized condition of these gases, quasar absorption lines in the rest-frame ultraviolet and X-ray regimes provide the most efficient observational probes of the CGM and IGM, but ultraviolet spectrographs offer vastly higher spectral resolution and sensitivity than X-ray instruments, and there are many more suitable targets in the UV, which enables carefully designed studies of samples of particular classes of objects. This white paper emphasizes the potential of QSO absorption lines in the rest-frame far/extreme UV at $500 \lesssim \lambda\text{rest} \lesssim 2000$ Å. In this wavelength range, species such as Ne VIII, Na IX, and Mg X can be detected, providing diagnostics of gas with temperatures $\gg 10^6$ K, as well as banks of adjacent ions such as O I, O II, O III, O IV, O V, and O VI (and similarly N I – N V; S II – S VI; Ne II – Ne VIII, etc.), which constrain physical conditions with unprecedented precision. A UV spectrograph with good sensitivity down to observed wavelengths of 1000 Å can detect these new species in absorption systems with redshift $z_{\rm abs} \gtrsim 0.3$, and at these redshifts, the detailed relationships between the absorbers and nearby galaxies and large-scale environment can be studied from the ground. By observing QSOs at $z = 1.0 - 1.5$, HST has started to exploit extreme-UV QSO absorption lines, but HST can only reach a small number of these targets. A future, more sensitive UV spectrograph could open up this new discovery space.

17. Ana Gomez de Castro, "Seeking into the anthropic principle"

The anthropic principle is about the emergence of life, of complex and intelligent life. For that, nucleosynthesis needs to have proceeded to enrich significantly the interstellar medium and guarantee that carbon, nitrogen, oxygen and phosphor are widespread in the Universe. Studies of the metal abundance variation up to redshift 5 are showing that the metallicity increases steadily with the age of the Universe. However there are numerous evidences of a large scatter in the metallic properties of matter for any given z; non metal-enriched clouds have been detected and chemically processed material has been found in the voids of the Comic Web. Meanwhile, the star formation rate seems, to be decaying from z=1. Important clues on the metal enrichment spreading on the Universe hang on inter-galactic transport processes such as galactic winds or the effect of galactic interaction in halos that are poorly studied because of the lack of high sensitivity imaging capabilities to detect the warm/hot plasma emission from galactic halos. Current information comes from absorption spectroscopy that it is a rather inefficient technique to map the large scales involved and requires the presence of strong background sources. Moreover, most of the emission is expected to come from filaments and chimneys that will require a high sensitivity imaging capability with resolutions at least ten times better than those provided by the GALEX mission.

18. Claudia Scarlata, "The escape fraction of ionizing photons from dwarf galaxies"

Measuring the escape fraction of ionizing photons from galaxies is a crucial step in understanding the reionization of the Universe, a central question in the COR program. We highlight how this goal can be achieved with deep imaging down to 2000Å (reaching NUV~32, i.e., about 10 times deeper than the currently deepest HST observations), over a large field of view (a few times Hubble's WFC3). We also briefly discuss the importance of deep spectroscopy in the NUV, to understand the mechanisms that allow the escape of ionizing radiation and to constrain the line-of-sight specific IGM absorption.

19. David Schiminovich, "Science from IGM/CGM Emission Mapping"

How does baryonic matter collapse, cool, form and fuel galaxies over cosmic time?" While the road to this answer may be tortuous, IGM emission mapping will provide a new perspective that could lead to fundamental breakthroughs by addressing these questions: 1) How strong is IGM emission, what is its relationship with absorption, and can emission mapping offer a new and powerful cosmological tool? 2) What is the total baryon content of the dark matter halos hosting galaxies in a 10^4-10^6K phase, and how does this gas content vary with redshift, galaxy type, evolutionary stage, and halo mass and environment? 3) How much CGM gas is inflowing to the galaxies, outflowing due to winds or AGN, replenished by inflow from the IGM? Do these gas flows regulate SF history, or are they regulated by star formation?

20. Stephan McCandliss, "Project Lyman: Quantifying 11 Gyrs of Metagalactic Ionizing Background Evolution"

> The timing and duration of the reionization epoch is crucial to the emergence and evolution of structure in the universe. The relative roles that star-forming galaxies, active galactic nuclei and quasars play in contributing to the metagalactic ionizing background across cosmic time remains uncertain. Deep quasar counts provide insights into their role, but the potentially crucial contribution from star-formation is highly uncertain due to our poor understanding of the processes that allow ionizing radiation to escape into the intergalactic medium (IGM). The fraction of ionizing photons that escape from star-forming galaxies is a fundamental free parameter used in models to "fine-tune" the timing and duration of the reionization epoch that occurred somewhere between 13.4 and 12.7 Gyrs ago (redshifts between $12 > z > 6$). However, direct observation of Lyman continuum (LyC) photons emitted below the rest frame H I ionization edge at 912 Å is increasingly improbable at redshifts $z > 3$, due to the steady increase of intervening Lyman limit systems towards high z. Thus UV and U-band optical bandpasses provide the only hope for direct, up close and in depth, observations of the types of environment that favor LyC escape. By quantifying the evolution over the past 11 billion years ($z<3$) of the relationships between LyC escape and local and global parameters such as: metallicity, gas fraction, dust content, star formation history, mass, luminosity, redshift, over-density and quasar proximity, we can provide definitive information on the LyC escape fraction that is so crucial to answering the question of, how did the universe come to be ionized? Here we provide estimates of the ionizing continuum flux emitted by "characteristic" ($L^*_{\rm uv}$) star-forming galaxies as a function of look back time and escape fraction, finding that at $z = 1$ (7.6 Gyrs ago) $L^*_{\rm uv}$ galaxies with an escape fraction of 1% have a flux of 10^{-19} ergs cm^{-2} s^{-1} Å^{-1}.

21. Gerard Kriss, "Synergistic Astrophysics in the Ultraviolet using Active Galactic Nuclei"

> Observing programs comprising multiple scientific objectives will enhance the productivity of NAS'□s next UV/Visible mission. Studying active galactic nuclei (AGN) is intrinsically important for understanding how black holes accrete matter, grow through cosmic time, and influence their host galaxies. At the same time, the bright UV continuum of AGN serves as an ideal background light source for studying foreground gas in the intergalactic medium (IGM), the circumgalactic medium (CGM) of individual galaxies, and the interstellar medium (ISM) and halo of the Milky Way. A well chosen sample of AGN can serve as the observational backbone for multiple spectroscopic investigations including quantitative measurements of outflows from AGN, the structure of their accretion disks, and the mass of the central black hole.

22. Steven Kraemer, "Active Galactic Nuclei and their role in Galaxy Formation and Evolution"

Nuclear super-massive black holes (SMBH) seem to be a fundamental constituent of galaxies. Their growth as active galactic nuclei (AGN) produces a significant fraction of the luminosity in the universe. Moreover, the masses of galactic bulges and SMBHs appear to correlated, which suggests the importance of the AGN in galaxy evolution (e.g., via AGN feedback). However, we face a basic limitation. AGN have been the archetypical "point sources" for 50 years: no spatial structure has been resolved in the inner regions in which the winds and jets involved in feedback processes arise. Space-based UV/optical interferometry is the only technologically feasible means to probe these inner regions.

23. Bradley Peterson, "UV Spectroscopic Time Domain Studies of Active Galactic Nuclei"

"Reverberation mapping" (Blandford & McKee 1982; Peterson 1993) is a spectroscopic time-domain technique that can be used to determine the structure and dynamics of the broad-line region (BLR) of AGNs. Reverberation mapping can provide us (a) with insights into mass outflows and mass accretion on microarcsecond scales, too small to be resolved by any other direct method, and (b) a means to directly measure the masses of the central black holes in these objects. Moreover, secondary methods anchored by reverberation mapping results allow us to estimate masses in active nuclei to arbitrarily large cosmic distances, addressing the Cosmic Origins goals of determining when supermassive black holes form and how have they affected the evolution of galaxies in which they are found. Indeed, all black hole mass estimates beyond the local universe are based on scaling relationships anchored by reverberation. In addition, the luminosities of AGNs can be inferred by BLR sizes determined by reverberation mapping, providing a direct measure of luminosity distances to quasars and allowing determination of cosmological parameters at redshifts as high as $z = 3$ or more.

24. Matthew Hayes, "Extragalactic Lyman-alpha Experiments in the Nearby Universe"

The universe has been statistically studied in the Hi Lyman-alpha emission line only at redshifts (z) above 2. Thus despite living in a universe where Ly-a is the brightest spectral feature of the most abundant species of baryonic matter, 75 per cent of our cosmic history is left unexplored. Here we outline the scientific case and approximate requirements for a space-based UV facility that could efficiently cover the remainder. Ly-a is the most important spectral beacon in high-z astrophysics, where studies of galaxy formation, the cosmic web, and the epoch of reionization all rely upon Ly-a population statistics. The unbiased assembly and study of a large sample of Ly-galaxies at low and moderate redshifts is the only method through which we can truly rely upon Ly-a as cosmological diagnostic tool. Simultaneously such observations would enable unprecedented studies of galaxy evolution and massive star formation across the latter 3/4 of cosmic time. A new UV-optimized mission with spectroscopic (R ~ 10,000) and spectrophotometric capabilities at λ = 1200- 3500Å is the only way that these goals can be realized. We therefore strongly recommend the inclusion of these capabilities in a future facility, and we are willing and able to contribute more detailed goals, requirements, and specifications and realistic simulations.

25. Paul Scowen, "Galaxy Assembly and SMBH/AGN-growth from Cosmic Dawn to the End of Reionization"

> In order to address the key Cosmic Origins science question "How did galaxies evolve from the very first systems to the types we observe nearby?", we propose to the community a systematic and comprehensive UV–near-IR cosmological broad- and medium-band imaging and grism survey that covers a wide area on the sky in multiple epochs. Specifically we advocate a tiered survey that covers <10 deg^2 in two epochs to m_{AB} <28mag, <3 deg^2 in seven epochs to mAB <29mag, and <1 deg^2 in 20 epochs to m_{AB} <30mag, each at 10σ point source sensitivity. Such a survey would provide spectrophotometric redshifts accurate to $\sigma_z/(1 + z) \lesssim 0.02$ and faint source variability measurements for $\gtrsim 5\times10^6$ galaxies and QSOs, and would be an essential complement to JWST surveys ($\lesssim 0.1$ deg^2 to $m_{AB} \lesssim 31$mag at λ >1100 nm and $z \lesssim 8$). This rich data set would allow: (1) study of faint Lyα-emitting and Lyman-break galaxies at $5.5 \lesssim z \lesssim 8$ to understand how galaxies formed from primordial density perturbations and to trace the metal enrichment of the intergalactic medium (IGM); (2) measuring the evolution of the faint end of the galaxy luminosity function (LF) from $z \sim 8$ to $z \sim 0$ by mapping the ramp-up of Pop II star formation, (dwarf) galaxy formation and assembly, and hence, the objects that likely completed the Hydrogen reionization by $z \simeq 6$; (3) direct study of the λ<91.2 nm escape fractions of galaxies and weak AGN from $z \sim 4.0$–2.5, during the epoch of Helium reionization; (4) measuring the mass and environment-dependent galaxy assembly process for $\gtrsim 5\times10^6$ galaxies from $z \simeq 5$ to $z \simeq 0$; (5) tracing the strongly epoch-dependent galaxy merger rate and constraining how Dark Energy affected galaxy assembly and the growth of super-massive black holes (SMBHs); (6) the study of $\gtrsim 10^5$ weak AGN, including faint variable objects (feeding SMBHs in the faint end of the QSO LF), over 10 deg^2 to measure how SMBH growth kept pace with galaxy assembly and spheroid growth, and how this process was shaped by various feedback processes over cosmic time. The proposed study is not feasible with current instrumentation but argues for a wide-field ($\gtrsim$250 $arcmin^2$), high resolution ($\lesssim$0.1″), UV–near-IR imaging facility on a 2.4–4m class space-based observatory.

26. Sara Heap, "A UV/Optical/Near-IR Spectroscopic Sky Survey for Understanding Galaxy Evolution"

> We outline the scientific benefits of a very large UV/Optical/near-IR spectroscopic survey for understanding the evolution of galaxies, circumgalactic medium, and intergalactic medium in the era of galaxy assembly (z>1).

27. Olivier Doré, "An Optical and Ultraviolet Cosmological Mapper"

> Working in the "intensity mapping regime" - large scale, low spatial resolution, moderate spectral resolution - optical and UV surveys offer a potentially very powerful, yet economical, avenue to map cosmological scales. The idea consists in mapping the aggregated line emission of many galaxies in a given frequency/redshift range rather than the emission of individual galaxies. To not aim at resolving individual galaxies naturally allows the use of a smaller telescope and also increases the signal strength, thus decreasing sensitivity requirements.

28. Charley Noecker, "Exoplanet Science of Nearby Stars on a UV/Visible Astrophysics Mission"

Direct imaging of nearby planetary systems will enable three broad science areas: (1) detection of individual exoplanets; (2) spectral characterization of those exoplanets, including searching for signs of life; and (3) investigation of the origin and ultimate fate of planetary systems. 1) The detection of individual exoplanets requires a high contrast imaging capability (e.g. internal coronagraph or external starshade), and can be accomplished with only a few snapshot images of the area around a star. 2) The spectral characterization of individual exoplanets begins with a longer observation for modest resolution spectroscopy ($\lambda/\delta\lambda \sim 70$-100), and should be followed by observations over a time span approaching or exceeding an orbital period, to obtain position, photometry, and spectroscopy as a function of time. 3) The investigation of the origin and evolution of planetary systems combines the information from the detection and characterization phases with our experience with the thousands of planets and candidates in the Corot, Kepler, RV, and gravitational microlensing surveys, and our knowledge of the specific planet-disk and planet-planet orbital interactions that are implied from many of the precise timing events from Kepler.

29. Timothy Cook, "Ultraviolet imaging of exoplanets"

Direct exoplanet observations are nominally the province of the EXOPAG and are thus beyond the scope of this RFI. However, the authors feel that given the synergy between exoplanet observations in general, and direct ultraviolet imaging of exoplanets in particular, and ultraviolet astrophysics that this response is warranted. The study of extrasolar planets is one of the most exciting endeavors of modern science. The statistics are familiar and impressive. To date over 750 planets have discovered in about 600 planetary systems — and that is not counting the thousands of Kepler planet candidates awaiting confirmation. The advent of high quality ultraviolet transiting observations and possibly more, better, ultraviolet observations in the future go a long way to furthering our understanding of the diverse properties of exoplanetary atmospheres. They have given us information about the composition, ionization, and dynamics (including the rates of atmospheric escape) of the atmospheres of a few planets.

30. Kevin France, "From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy"

> Few scientific discoveries have captured the public imagination like the explosion of exoplanetary science during the past two decades. This work has fundamentally changed our picture of Earth's place in the Universe and led NASA to make significant investments towards understanding the demographics of exoplanetary systems and the conditions that lead to their formation. The story of the formation and evolution of exoplanetary systems is essentially the story of the circumstellar gas and dust that are initially present in the protostellar environment; in order to understand the variety of planetary systems observed, we need to understand the life cycle of circumstellar gas from its initial conditions in protoplanetary disks to its endpoint as planets and their atmospheres. In this white paper response to NASA's Request for Information "Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts (NNH12ZDA008L)", we describe scientific programs that would use the unique capabilities of a future NASA ultraviolet (UV)/visible space observatory to make order-of-magnitude advances in our understanding of the life cycle of circumstellar gas.

31. Michael Wong, "Solar System Science Objectives with the Next UV/Optical Space Observatory"

> NASA's Great Observatories (and smaller space telescopes) enable a wide range of solar system science investigations, particularly in the ultraviolet, optical, and infrared ranges. These investigations are an important part of the Cosmic Origins program, providing a local reference point for the origin and evolution of stars and planetary systems. The next UV/optical space observatory can drive fresh insights into the origin and evolution of the solar system, if the technical requirements for planetary observations are met. These requirements are easily achieved via the groundwork that has already been done for HST and JWST.

32. Patrick Côté, "Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths"

> A wide-field (0.5-1 sq. deg.), ~1m-class space telescope that provides nearly diffraction-limited imaging (FWHM ~ 0.153) at UV/blue optical wavelengths (0.15–0.55 μm) has the potential to make a unique, powerful, and lasting contribution to modern astrophysics. Such a mission would be a natural successor to both the Hubble Space Telescope (HST) and the Galaxy Evolution Explorer (GALEX), and would far surpass any ground-based optical telescope in terms of angular resolution. It would also provide crucial "UV/blue" imaging to supplement longer-wavelength data from future dark energy space missions (Euclid, WFIRST) as well as from the ground-based Large Synoptic Survey Telescope (LSST). For maximum scientific impact and complementarity with Euclid/WFIRST, the facility should allow the implementation of GO/PI programs, but concentrate initially on a small number of "legacy" surveys – including a "wide survey" that would cover an area of at least ≈5000 deg^2, in three filters, to depths of ≈ 25.8 mag (UV), 27.1 (u) and 27.8 (g). We review the rich and diverse science investigations that such a wield-field imaging facility would enable, which include (but are not limited to) dark energy, galaxy evolution, near-field cosmology, stellar astrophysics, the outer solar system, and time-domain astronomy.

33. Jason Tumlinson, "Unique Astrophysics in the Lyman Ultraviolet"

> There is unique and groundbreaking science to be done with a new generation of UV spectrographs that cover wavelengths in the "Lyman Ultraviolet" (LUV; 912 - 1216 Å). There is no astrophysical basis for truncating spectroscopic wavelength coverage anywhere between the atmospheric cutoff (3100 Å) and the Lyman limit (912 Å); the usual reasons this happens are all technical. The unique science available in the LUV includes critical problems in astrophysics ranging from the habitability of exoplanets to the reionization of the IGM. Crucially, the local Universe ($z \lesssim 0.1$) is entirely closed to many key physical diagnostics without access to the LUV. These compelling scientific problems require overcoming these technical barriers so that future UV spectrographs can extend coverage to the Lyman limit at 912 Å.

34. Melville Ulmer, "White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)"

> This paper describes how it is possible to gain better than a factor of 10 in sensitivity with the same size mirror as HST. Technology investments are needed, however. I further list a few science drivers for a new improved UV-Vis mission.

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Contributions to COR science objectives:

- When did the first stars in the universe form, and how did they influence their environments?
- What are the mechanisms by which stars and their planetary systems form?
- How are the chemical elements distributed in galaxies and dispersed in the circumgalactic and intergalactic medium?

This science objective contributes to the above objectives by trying to understand how molecules and dust cores form in massive winds. At high redshifts, evidence is that metal enrichment and dust occurred early after the first stars formed. We simply do not understand how the dust cores form in stellar atmospheres, enriched by carbon and oxygen the basic building blocks for many molecules. Yet molecular and dust formation is so robust that both form even in stars with greatly depleted amounts of carbon and oxygen, as exemplified by Eta Carinae. Massive stars, that evolved rapidly, must play a dominant role in chemical enrichment early in the Universe. By studying current day systems, we can gain insight on the earliest mixing in young galaxies.

How do molecules and dust form in massive interacting winds?

One of the mysteries of interstellar dust is how it forms. While prodigious amounts of dust are seen in the interstellar medium, most models assume a dust core and then proceed to build a mantle of condensed molecules around this core.

What are the sources of the dust cores? Most likely come from relatively cool stars that have evolved over a lengthy period, producing prodigious amounts of carbon and oxygen through the CNO process. However we find massive amounts of dust around evolved massive stars, most notably evolved massive binary systems. The amount of UV and visible radiation should prevent the formation of molecules and dust, yet dust is present. Evolved massive stars with large amounts of carbon and oxygen, as seen, would be expected to form molecules and dust. But how does dust form in massive stars with greatly depleted carbon and oxygen?

Such is the case with the massive binary, Eta Carinae. In the Great Eruption of the 1840s, huge amounts of material were ejected by this very evolved binary. Today that ejecta, know as the Homunculus, expands outward at 600 km/s, and is seen on the sky by reflected starlight… by dust formed at the time of the eruption. The central source, measured to have a luminosity of $5x10^6$ solar luminosities, is occulted by five magnitudes, thought to be dust actively being formed in the current interacting winds.

With Herschel, we have found evidence for many molecules despite the fact that carbon and oxygen are depleted nearly 100-fold relative to solar abundances. The identified molecules and their abundances are extraordinarily different from abundances in molecular clouds or ejecta from massive stars with normal abundances. How did dust form in the Great Eruption and continue to form in the interacting winds when carbon and oxygen are so depleted? Is the dust different in composition? Is the dust formation process far more robust that we think?

The Space Telescope Imaging Spectrograph on Hubble, with 0.1" angular resolution and 8000 resolving power, has provided spatial-velocity data cubes of forbidden line emission originated from Fe, N, O, S, Ne at visible wavelengths. Such has inspired very detailed three-dimensional hydrodynamic models of the interacting winds as we attempt to located regions in the compressed winds where molecules and dust might form. At larger scales, the 20"-sized Homunculus has been studied in detail to understand the spatial structure of the expanding material. From Herschel, we have found dozens of molecules in this outer structure that appear to co-exist in either a layered, or clumped, environment. Both the central binary source with its massive interacting winds and the expanding Homunculus are evolving noticeably with time.

Selected HST/STIS forbidden line data cubes have been matched with synthetic emission data cubes derived from the three-dimensional hydrodynamic models at specific phases of the 5.5-year binary period, As the forbidden line emission is dependent upon FUV radiation and critical densities, we are able to probe the interacting winds and with the models, we are able to isolate compression regions, that, with radiative transfer, indicate where the densities and temperatures would promote molecular and dust formation.

Three areas of improvement are necessary to dig deeper into this problem:

1) Higher spatial resolution. Factors of 2 – 10 would lead to improved definition of regions where molecules and dust form. The binary orbit is thought to have a 0.010" semi-major axis (and the interacting winds serve as a major amplifying factor to the scale that HST/STIS resolves the winds). The compression regions should have scales of this amplitude.
2) Improved throughput throughout the visible and UV. HST/STIS, because of desire to have diffractive-limit spatial resolution and the corrective optics, required multiple reflective surfaces. Improved optical design, potentially totally different photonics designs (fiber optic concepts??), and improved reflectivity must be developed.
3) Multi-aperture optical system and larger format visible/UV detector. HST/STIS, with its imaging capability and long slit designs provided the ability to map complex systems such as the interacting winds. However, building a 2.4"x2.4" map with 0.1" spatial resolution, optimally sampled at 0.05", required nearly a full HST CVZ orbit for individual 30 second exposures.

The Importance of White Dwarf Stars as Tests of Stellar Physics and Galactic Evolution

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Introduction

Every star will meet one of three ends as it approaches the limits of its evolution. If the star is massive, the events triggered by the exhaustion of nuclear fuel in the stellar core will lead to a black hole. If the star is of intermediate mass, the product will be a neutron star. If the star is low mass, the end product will be an electron-degenerate white dwarf. The overwhelming majority of all stars formed in previous stellar generations, those currently on the main sequence including our Sun, and stars born in the future have or will end their lives as white dwarfs.

White dwarfs are structurally simple objects. Ninety nine percent of a white dwarf's mass is contained in an electron-degenerate core. High surface gravities (log g $\sim$ 8 in cgs) and efficient chemical diffusion/gravitational settling produce atmospheres composed predominantly of either hydrogen (DAs) or helium (DBs). DA white dwarfs comprise 80% of the total population and helium dominant DBs the remaining 20%. Evidence provided by ultraviolet and asteroseismological investigations increasingly supports the idea that DAs and DBs follow separate evolutionary paths. We now believe that once DAs emerge onto the white dwarf cooling track (with hydrogen layer masses between $M_H \sim 10^{-7} M_*$ and $M_H \sim 10^{-4} M_*$), they remain DAs as they cool (Bergeron 1995)). DBs are not as numerous as DAs and consequently are more difficult objects to study. Fundamental questions about their atmospheres, origins, and evolution remain (Bergeron 2011).

White dwarfs are rich forensic laboratories that provide links between the history and future evolution of the Milky Way Galaxy. The structure and composition of white dwarfs contain the records of the final stages of stellar evolution. As a newly forming white dwarf evolves through the planetary nebula phase, large quantities of processed material are injected into the interstellar medium. The chemical evolution of the Galaxy is traced through subsequent generations of stars formed from this contaminated material. The current temperature and/or luminosity distribution of Milky Way white dwarfs constrains models of galactic and cosmological evolutionary history. Type I supernovae, in which an accreting white dwarf undergoes a thermonuclear event, are used as distance indicators demonstrating the acceleration of the universe. Underlying all these studies is the theoretical mass-radius relation for electron degenerate matter. An important consequence of this relation is the existence of a limiting mass for white dwarf stars.

UV astronomy is particularly important for the study of white dwarf stars. A significant fraction of white dwarf emergent flux appears in the UV, especially for the hotter stars. In addition, traces of elements heavier than hydrogen or helium are, in general, only detected in this waveband or at shorter wavelengths that are also only accessible from space. In the following, we will broadly outline the importance of the white dwarf mass-radius relation, the white dwarf luminosity function, and white dwarf spectroscopy in understanding important cosmological questions, including questions of stellar physics in extreme conditions, galactic evolution, stellar formation and evolution, and the chemical distribution of material in our galaxy. We will conclude by demonstrating the importance of UV observations of white dwarf stars in advancing our understanding of these questions.

The White Dwarf Mass-Radius Relation

The theoretical mass-radius relation for electron degenerate matter is a generally accepted underlying assumption in all studies of white dwarfs and their properties. In turn, these studies, including the white dwarf mass distribution and luminosity function, are foundations for such fields as stellar evolution, galactic formation and Type 1a supernovae. The relation predicts the radius of a white dwarf of given mass and interior composition, usually assumed to contain a mixture of carbon and oxygen. An important consequence of the mass-radius relation is the limiting mass for white dwarfs (Chandrasekhar 1933), above which an object cannot be supported by electron degeneracy.

One would like to assume that as fundamental a theory as the white dwarf mass-radius relation rests on solid observational grounds. However, we have complete observational data for only 3 stars (40 Eri B, Procyon B, and Sirius B). Each of these objects is a member of a binary system, giving us the ability obtaining independent dynamical information on the white dwarf mass from its orbital parameters. In addition, the stellar distances are known, allowing for an independent determination of stellar radii (Figure 1). The source of difficulties for single white dwarfs is the need for determinations of masses and radii in ways that do not invoke the mass-radius relation.

The most general method used to determine white dwarf masses, and the single technique capable of inferring the masses of solitary white dwarfs, is the comparison of observed spectra with the predictions of model atmospheres. This comparison produces estimates of surface gravity (log g) and effective temperatures by matching the widths of line profiles. Precise surface gravities are essential, as the uncertainty in log g translates directly into the mass uncertainty. However, surface gravity is a function both of mass and of radius. Most field white dwarfs do not have the accurate parallax measurements necessary for deriving precise independent radii. In addition, surface temperature can be influenced by trace elements, most of which are only detected in the UV wavelength range. In most cases, to determine stellar mass one must assume an underlying mass-radius relation for a given core composition, usually chosen to be carbon. It is therefore difficult to prove the validity of the mass-radius relation without assuming its existence (Provencal 2002).

The White Dwarf Luminosity Function

White dwarf evolution is dictated by cooling. White dwarfs contain no energy sources, and cool by emitting residual energy. As any white dwarf cools, its surface temperature decreases and its luminosity decreases. White dwarfs have very small surface areas, so they cool very gradually over billions of years. The basic analytical model of white dwarf cooling was developed by Mestel in 1952.

The observed white dwarf luminosity function (WDLF) is defined as the number of white dwarfs as a function of their intrinsic luminosity (Figure 2). The WDLF is a convolution of the star formation history of the Galaxy, the cooling physics of white dwarfs, and the evolution of the white dwarf progenitors. As such, it is a valuable diagnostic of the age of the galactic disk and the history of stellar formation in the Galaxy. Detailed knowledge of the white dwarf cooling can provide a valuable cosmic

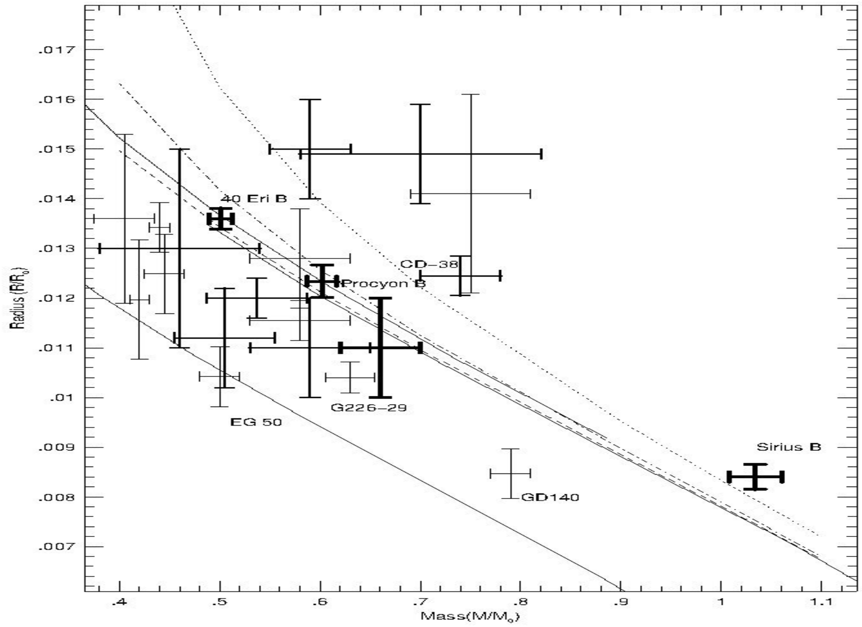

Figure 1: Current observational support. Positions of the visual binaries Procyon B, Sirius B, 40 Eri B, and Stein 2051B (extra-thick error bars), common proper motion systems (thick error bars), and field white dwarfs (thin error bars) are shown (from Provencal et al. 2002).

clock to determine the ages of individual white dwarfs, the ages of open and globular clusters, and age of the galactic disk.

Upcoming as well as ongoing surveys (SDSS, LSST) will greatly improve the white dwarf sample and hence the empirical luminosity function. We will require detailed observational support for these new objects. In particular, the hotter and cooler ends of the WDLF contain few objects. This can be attributed to the difficulty in identifying the coolest white dwarfs, and the relative rarity of hot white dwarfs. UV observations will be particularly important for the hotter objects.

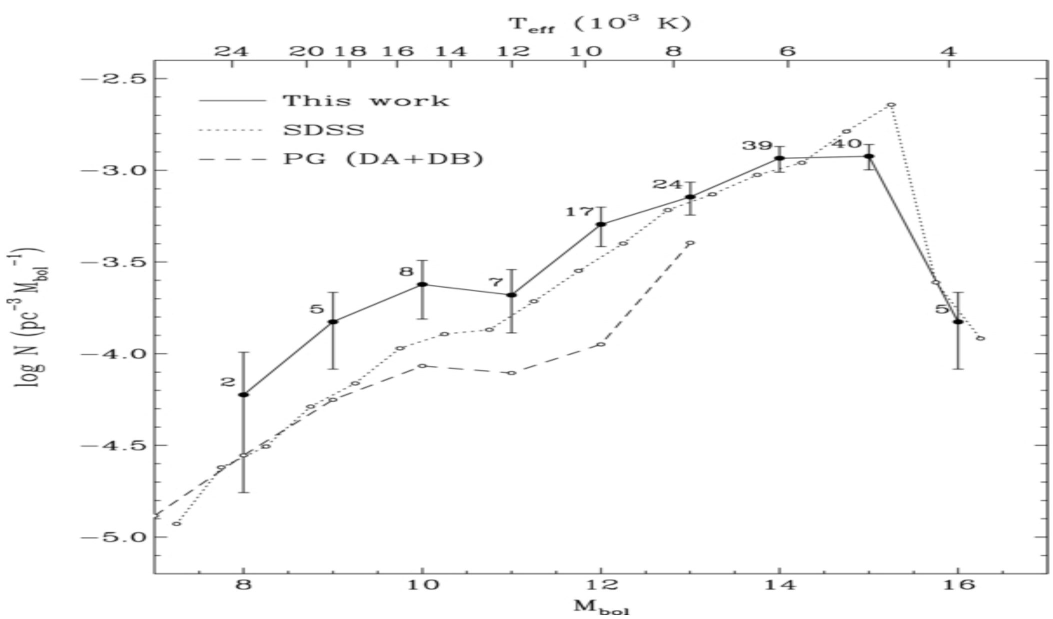

Figure 2: Luminosity function (solid line) from Giammichele et al. (2012), compared to the luminosity functions obtained from the SDSS (Harris et al. 2006) (dotted line) and the PG survey (dashed line, Bergeron et al. 2011) for the DA and DB stars in the PG survey (dashed line). The temperature scale assuming M= 0.6 is also shown at the top of the figure.

Photospheric Composition of White Dwarf Atmospheres and the Interstellar Medium

It is well established that some white dwarfs, particularly the hotter objects, possess significant abundances of elements heavier than helium in their atmospheres. Given the high surface gravities and short diffusion timescales, the favored origin for these trace elements is accretion from the interstellar medium. In addition, the lack of hydrogen in most DB white dwarfs, which have been immersed in the hydrogen dominated interstellar medium, is an unresolved question.   Finally, white dwarfs are important probes of the structure and composition of the local interstellar medium. Lehner et al. (2009) present detailed results of a survey of the local interstellar medium using 31 white dwarfs observed with the FUSE satellite.

The Importance of UV Observations of White Dwarf Stars

We now arrive at the primary motivation for this discussion: our continuing need for UV observations of white dwarf stars to address problems of importance to a wide range of astronomical fields. Direct imaging in the UV is an significant method of discovering new objects, especially including white dwarfs in binary systems. As an example, a major result of the EUV sky surveys was the discovery of many unresolved binary systems containing white dwarfs and companions with spectral types ranging from A to K (see for example Barstow et al. 1994). In optical wavelengths, the presence of a companion of spectral type earlier than mid-K will swamp the white dwarf, making it undetectable. In the EUV, the companion flux is generally negligible, and the white dwarf stands out very clearly. The UV wavelength range is an even more efficient way of searching for these binaries, as the interstellar opacity is much lower than in the EUV and the GALEX sky survey is finding many examples.

Ultraviolet spectroscopic observations have played an essential role by providing access to absorption features from elements heavier than He. These features are not usually present in optical or infrared data except where photospheric abundances are unusually high. Typical detection limits in the UV are two orders of magnitude lower. Therefore, the most important and useful transitions, particularly many resonance lines of elements heavier than H and He, lie in the far-ultraviolet (far-UV, 1000-2000Å).

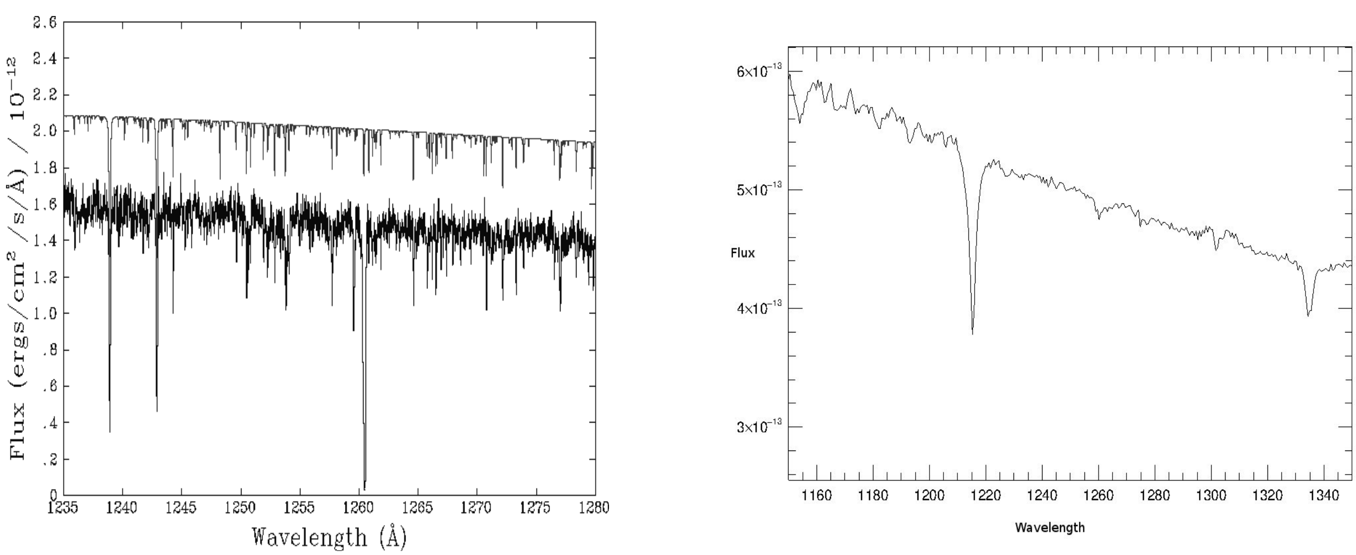

Figure 3: Left: STIS spectrum of REJ0558-373, showing photospheric absorption lines of NV (1238.821/1242.804Å) and large numbers of Ni lines. The best-fit synthetic spectrum is shown offset for clarity. The strong line near 1260Å,

present in the observation but not in the model, is interstellar SiII (from Barstow et al. 2003). Right: STIS spectrum of GD358, showing Lyman α, and CII at 1335 Å.

However, since the lines are expected to be weak and narrow, they are only normally visible at high resolution (R>20,000). An example is given by the hydrogen atmosphere white dwarf REJ0558-373. Fig. 3 shows the high-resolution spectrum obtained with the Space Telescope Imaging Spectrograph onboard *HST*, which includes the interstellar 1260.4 Å line of SiII together with photospheric NV. A second example is given by the helium atmosphere DB GD358, which shows absorption features of CII.

Determinations of the physical properties of white dwarf stars such as temperature and surface gravity is severely hampered by the large errors associated with optical spectroscopic determinations, especially for hotter white dwarfs and helium atmosphere objects (DBs). Most of this error is not due to failings of the optical spectroscopic observations and resulting model fits, but rather to the high temperatures of the objects. For example, optical spectroscopy of helium white dwarfs with temperatures cover regions far out on the Rayleigh-Jeans tail of the energy distribution. This creates difficulties in properly defining the observed continuum (Figure 4, left). In addition, in this temperature range, optical helium lines are insensitive to changes in temperature (Fig. 3, right). Finally, trace amounts of hydrogen and other elements particularly affect the DB temperature scale. Beauchamp et al. (1999) show fitting a pure helium model to a star containing traces of hydrogen (H/He ~10^{-4}-10^{-5}) can produce changes in effective temperatures as large as 3000 K. Upper limits on hydrogen abundances do exist (Bergeron et al. 2011), but detection of trace amounts in DB white dwarfs is notoriously difficult at optical wavelengths.

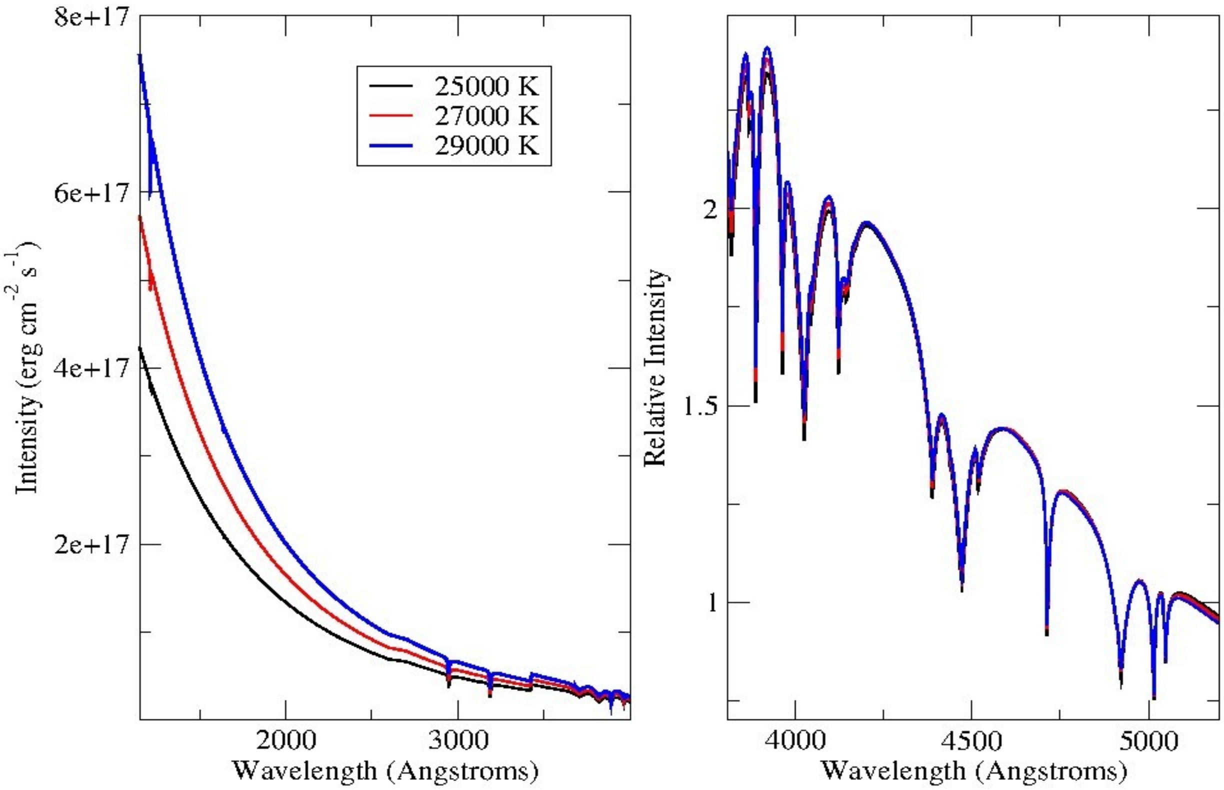

Figure 4: Synthetic spectra of pure helium DB models (log g = 8 and ML2) at 25000, 27000, and 29000 K. The left panel shows the effects of increasing temperature on the slope shortward of 3000 Å, while the right panel shows the

insensitivity of optical helium lines to changes in effective temperature.

Finally, the hottest white dwarfs, the PG1159 stars, are rare objects. Only a select few have been studied in detail in the ultraviolet. High-resolution UV observations are essential, because most diagnostic metal lines observed in these extremely hot stars are located in this wavelength region. The wide spread in element abundances, as well as the observed iron-deficiency and neon- and fluorine-overabundances show that PG1159 stars have a large, and unique, potential to study mixing and fusion processes whose consequences are usually unobservable in other stars. As a consequence of a late He-shell flash, PG1159 stars exhibit intershell matter that normally remains hidden in the stellar interior. In contrast to cooler white dwarfs, the observed element abundances in PG1159 stars are not affected by gravitational settling, hence, abundance patterns still do reflect the history of these stars.

Conclusions

White dwarfs represent a significant contribution to the galactic stellar population and are significant indicators of the evolutionary history of the Galaxy. It is critical to understand the white dwarf population as fully as possible. This is only possible through a continued program of observations in the far ultraviolet waveband. Given the current and upcoming survey projects, our principal need is for high resolution spectroscopy, but diffraction limited imaging is also of importance.

The situation regarding continued access to the far UV after HST is overshadowed by complex programmatic and political issues which make it difficult to plan ahead. Currently, no space agency has any plans for a HST (or larger) class UV telescope. To achieve this in a relatively short timescale requires the use of existing technology, but given that HST itself is “old” technology, it should be possible to provide an instrument with enhanced sensitivity through avoidance of complex relay optics and significantly improved grating and detector technology. A 2-m class telescope would be able to address many of the science goals relating to observation of white dwarfs in our own galaxy if the following technical capabilities are achieved:

- Galactic white dwarf spectroscopic survey
  - λ~912-3000Å, R~50,000-100,000, V_{lim}~20
- Astrometric white dwarf masses
  - Diffraction limited imaging to V~20

For a larger 4-6 m telescope, white dwarf research would be greatly advanced by these key requirements:

- Globular cluster/Magellanic Cloud white dwarf surveys
  - Integral field spectroscopy λ~912-1300Å, R~1000, V_{lim}~28
  - Wide field imaging (10 arcmin) to V~35

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The Origin of the Elements Heavier than Iron

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A white paper written in response to the RFI for "Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts"
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1. Science Motivation

Understanding the origin of the elements is one of the major challenges of modern astrophysics. This goal is expressed in several of the Cosmic Origins science questions, including how the first stars influenced their environments, how the chemical elements were dispersed through the circumgalactic medium, how galaxies and their constituent stars formed and evolved, and how baryons destined to form planets grow to heavy atoms.

The metals in a star today are a snapshot of the metals in the interstellar medium (ISM) at the time and place where that star was born. Ancient halo stars offer the opportunity to make a reasonable connection between individual stellar nucleosynthesis events and the metal distributions found in the oldest stars. The elements heavier than iron, which have been detected in the ancient stars of the Galactic halo, in the ISM, dust grains, meteorites, and on Earth, are formed by neutron-capture reactions.

Relatively low neutron densities found in the He-rich inter-shell of AGB stars lead to heavy element nucleosynthesis by the slow neutron-capture process (s-process). Relatively high neutron densities lead to heavy element nucleosynthesis by the rapid neutron-capture process (r-process). Despite decades of analytical work and countless simulations, there are no definitive observations linking high-mass r-process material with an astrophysical site or sites of nucleosynthesis. Observations of Ba and Sr in SN 1987A have strengthened the case for production of some r-process material in core-collapse supernovae. In addition to the long favored core-collapse supernovae sites, there are now reasonable but unproven models of r-process nucleosynthesis in neutron star plus neutron star or black hole mergers and more exotic events such as quark novae.

One way to better constrain the physical conditions at the nucleosynthesis sites of the s-process and r-process is to study the complete atomic mass distribution produced. More than 25 elements heavier than the iron-group can be reliably detected in high-resolution, high-S/N optical spectra of late-type (FGK) stars obtained from ground-based facilities. Another 11 elements (including Ge, As, Se, Cd, Te, Lu, Os, Ir, Pt, Ag, and Pb) can be reliably detected in similar quality near-UV spectra. The near-UV spectral window offers the only opportunity to reliably detect these particular elements, which include some of those providing the most sensitive constraints on the nucleosynthesis models. These models, in turn, constrain the conditions at the astrophysical site(s).

The Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST) continues to be an effective tool for performing this kind of work. Several relevant examples of this science may be found in Sneden et al. (1998, Astrophys. J., 496, 235), Cowan et al. (2005, Astrophys. J., 627, 238), and Roederer & Lawler (2012, Astrophys. J., 750, 76). Yet, many interesting stars lie at distances too great for practical observations with HST+STIS, including stars with the highest levels of r-process enrichment, stars with severe deficiencies of r-process and s-process material, stars with unexplained deviations from the r-process and/or s-process abundance patterns, and the most iron-poor stars known (at least one of which contains substantial doses of elements heavier than the iron-group).

2. Requirements

The spectral region between 1900 Å and 3050 Å contains dozens of neutron-capture absorption lines that have been demonstrated to be good abundances indicators. Figure 1 illustrates this point for three Se I lines in the STIS spectrum of one metal-poor subgiant, HD 160617. Useful lines are widely spaced from 1900 Å to 3050 Å, so a future spectrograph would be most effective if it could record this entire wavelength region (or at least half of it) in a single observation.

High spectral resolution ($R \equiv \lambda/\Delta\lambda$) is essential. $R \sim$ 60,000 (5 km s^{-1}) is sufficient to resolve the lines. $R \sim$ 100,000 is ideal to oversample the line profile to resolve the many blended features in the near-UV, and $R \sim$ 30,000 is the minimum acceptable resolution.

Although any facility that meets these spectral and bandpass requirements will be of some use, a true step forward will require an overall telescope plus instrument throughput at least 10 times better (telescope aperture, optical transmission, detector quantum efficiency, etc.) than HST+STIS at these wavelengths. This would enable substantially larger samples of local stars (within $\sim$ 400 pc) or individual stars with demonstrated nucleosynthetic value at significantly greater distances (up to $\sim$ 6 kpc) to be observed in integration times comparable to successful observing campaigns with HST. Either of these approaches would offer an opportunity to address the scientific goals described in Section 1.

Modern surveys have already identified large numbers of disk and halo stars whose near-UV spectra would surely reveal valuable nucleosynthetic information. The field density of metal-poor stars is generally quite low, of order 1 star per 3 deg^2 down to $B \approx 16$ toward the Galactic poles, so multiplexing offers no advantage in most cases. High throughput and wide bandpass are preferable to object multiplexing, though such capability ($\sim$10 or more objects) could be useful for limited applications (e.g., Galactic globular or open clusters) with a modest field of view of $\sim$ 10 $\times$ 10 arcmin.

An instrument with these capabilities should allow for verification and cross-checks of neutron-capture element abundance patterns in a variety of astrophysical environments.

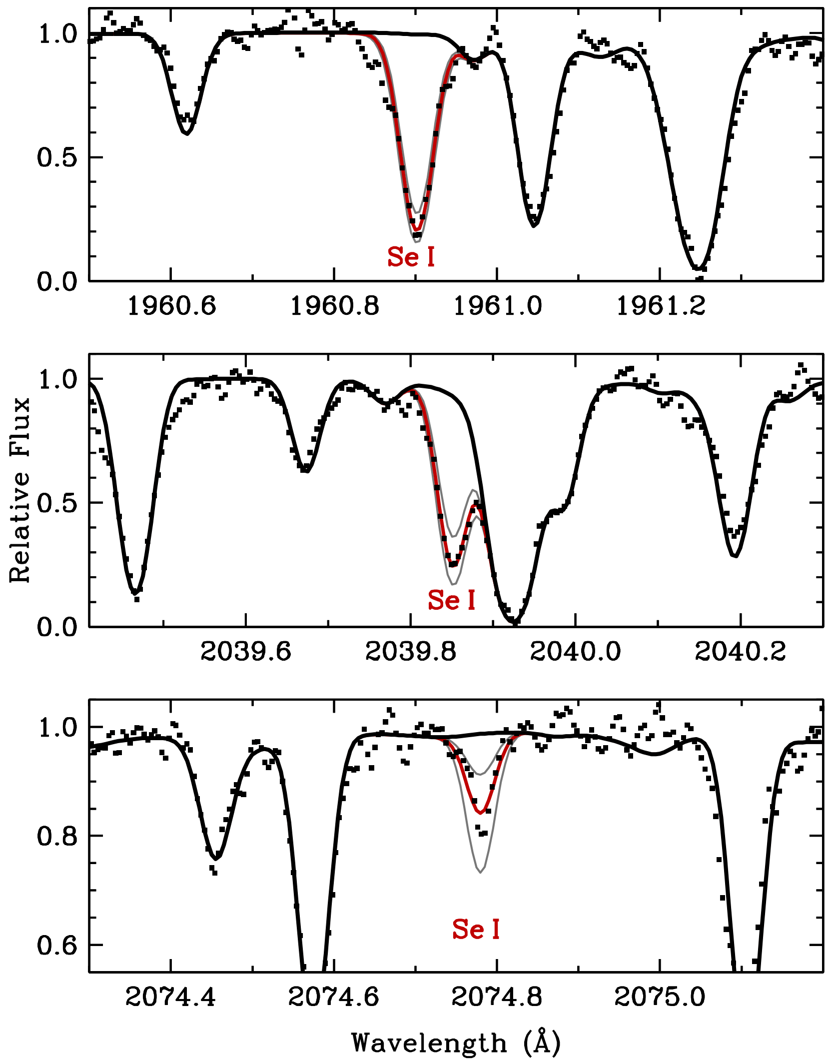

Fig. 1.— Three Se I lines in the STIS spectrum of the metal-poor subgiant HD 160617. This spectrum has $R \sim 110{,}000$ and S/N $\sim$ 30 to 50 pixel^{-1}. Overlaid synthetic spectra represent the best-fit abundance (red), factors of 2 variations (gray), and a synthesis with no Se present (black). This is Figure 6 of Roederer & Lawler (2012, Astrophys. J., 750, 76).

3. Summary

Understanding the origin of the elements heavier than iron remains one of the major challenges in modern astrophysics, and high-resolution near-UV spectroscopy offers an opportunity to detect elements that can constrain the unconfirmed astrophysical site(s) of r-process nucleosynthesis. The availability of high-resolution ($\lambda/\Delta\lambda > 30{,}000$) and high S/N ($\gtrsim 50$) near-UV ($1900 < \lambda < 3050\,\mathrm{\AA}$) spectra presently allows for a 40% increase in the number of elements heavier than the iron-group that can be detected in late-type stars. In stars useful for interpreting the nucleosynthetic record, these elements can only be reliably detected in the near-UV. We recommend that any future space UV mission should include an instrument capable of achieving these spectral qualities in single-object observing mode in reasonable integration times for late-type stars within ~ 6 kpc of the Solar neighborhood.

J.E. Lawler is available to participate in a science objective workshop.

UVMag: Stellar physics with UV and visible spectropolarimetry

1 Administrative details and management

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The UVMag consortium includes scientists willing to design and promote space UV spectroscopy and spectropolarimetry to study stellar magnetospheres (winds, magnetic fields, confinement of circumstellar material,...). The consortium currently consists of over 20 active scientists from 16 different institutes (see Table 1), but of course many more scientists from these institutes or elsewhere are also interested in the project.

A UVMag website is available at http://lesia.obspm.fr/UVMag. It includes a detailed document describing the science goals and technical requirements of the UVMag project. In addition, **we would gladly present our science objectives and investigations at a NASA workshop if invited.**

2 Science rationale

2.1 Science drivers: stellar physics

We propose to study the formation, structure, evolution and environment of all types of stars in particular through the measurement of their magnetospheres, i.e. through the association of spectropolarimetry and spectroscopy in the UV and visible domains.

The UV domain is crucial in stellar physics because it is particularly rich in atomic and molecular transitions, and covers the region in which the intrinsic spectral distribution of hot stars peaks. The UV lines are the least influenced by non-LTE effects in stellar photospheres and are thus most useful e.g. for quantitative abundance determinations. The lower levels of these lines are less likely to depopulate in low density environments such as chromospheres, circumstellar shells, stellar winds, nebulae and the interstellar medium, and so remain the only useful diagnostics in most of these environments. Another advantage of observing in the UV is the extreme sensitivity of the Planck function to the presence of small amounts of hot gas in dominantly cool environments. This allows the detection and monitoring of various phenomena that would otherwise be difficult to observe: accretion continua in young stars, magnetic activity, chromospheric heating, corona, starspots on cool stars, and intrinsically faint, but hot, companions of cool stars. The UV domain is also the one where Sun-like stars exhibit their hostility (or not) to Earth-like life, population 0 stars must have shone the brightest, accretion processes convert much kinetic energy into radiation which strongly

Table 1: Active consortium members

Members	Institute	Email	Expertise
E. Alecian	LESIA, France	evelyne.alecian@obspm.fr	Herbig stars
T. Ayres	Univ. Colorado, USA	thomas.ayres@colorado.edu	Cool stars
D. Baade	ESO-HQ, Germany	dbaade@eso.org	Be stars
S. Bagnulo	Armagh Obs., UK	sba@arm.ac.uk	Ap/Bp stars
J.-C. Bouret	LAM, France	jean-claude.bouret@oamp.fr	O stars
D. Cohen	Swarthmore Coll., USA	cohen@astro.swarthmore.edu	X-rays
L. Drissen	Univ. Laval, Canada	ldrissen@phy.ulaval.ca	Wolf-Rayet stars
A. Fullerton	STScI, USA	fullerton@stsci.edu	O stars
C. Gry	LAM, France	cecile.gry@oamp.fr	ISM
G. Hussain	ESO-HQ, Germany	ghussain@eso.org	T Tauri stars
O. Kochukhov	Univ. Uppsala, Sweden	oleg@astro.uu.se	Surface imaging
J. Landstreet	Armagh Obs., UK	jlandstr@astro.uwo.ca	Ap/Bp stars
S. Mathis	CEA, France	stephane.mathis@cea.fr	Theory
G. Meynet	Univ. Geneva, Switzerland	georges.meynet@unige.ch	Structure/evolution
R. Monier	Univ. Nice, France	richard.monier@unice.fr	A stars
J. Morin	Univ. Göttingen	jmorin@gwdg.de	M stars
C. Neiner	LESIA, France	coralie.neiner@obspm.fr	Hot stars
N. Piskunov	Univ. Uppsala, Sweden	piskunov@astro.uu.se	Surface imaging
C. Robert	Univ. Laval, Canada	carobert@phy.ulaval.ca	Stellar formation
P. Petit	IRAP, France	petit@ast.obs-mip.fr	Cool stars
T. Rivinius	ESO, Chile	triviniu@eso.org	Be stars
M. Smith	STScI, USA	msmith@stsci.edu	γ Cas stars
R. Townsend	Wisconsin, USA	townsend@astro.wisc.edu	Magnetospheres
G. Wade	RMC, Canada	wade-g@rmc.ca	Hot stars
A. ud-Doula	Penn State Univ., USA	asif@psu.edu	MHD simulations

impacts stellar formation and evolution, the "Fe curtain" features respond to changes in local irradiation, etc.

In addition, most of cool stars and a fraction of hot stars are magnetic and their magnetic field interacts with their wind and environment, modifies their structure and surface abundances, and contributes to the transport of angular momentum. With spectropolarimetry, one can address with unprecedented detail these important issues in stellar physics, from stellar magnetic fields to surface inhomogeneities, surface differential rotation to activity cycles and magnetic braking, from microscopic diffusion to turbulence, convection and circulation in stellar interiors, from abundances and pulsations in stellar atmospheres to stellar winds and accretion disks, from the early phases of stellar formation to the late stages of stellar evolution, from extended circumstellar environments to distant interstellar medium. Moreover, measuring polarization directly in the UV wind-sensitive lines has never been done, and would be extremely useful in order to trace the polarization along the field lines. Finally, polarimetry is not restricted to magnetic fields only. The scope of stellar polarimetry is much broader, in particular with respect to circumstellar processes.

The spectropolarimetric capability, both in the UV and visible wavelength domains, will therefore nicely complement the spectrograph to multiply tenfold the capabilities of extracting information on magnetospheres, winds, disks, and magnetic fields. The UV+visible spectropolarimeter will consequently provide a very powerful and unique tool to study most aspects of stellar physics in general and in particular for stellar formation, structure and evolution as well as for stellar environment. In particular, it will help to answer the following long-standing as well as new questions:

Stellar formation

- What are the statistical properties of the various populations of stars? What is the incidence of magnetic fields? What are the properties of wind and mass loss?
- What causes the segregation of tepid stars in two categories: those with sub-gauss magnetic fields (Vega-like stars) and those with fields above a few hundred of Gauss (Ap/Bp stars)? Why are there no tepid stars with intermediate strength field?
- What are the timescales over which magnetospheric accretion stops in pre-main sequence (PMS) stars?
- Why do T Tauri stars rotate slowly? How does the disk locking mechanism work?
- What happens during the magnetic stabilization phase at the start of the PMS? How does an abrupt change of magnetic obliquity affect the star and its environment?

Stellar structure

- In which conditions does a dynamo magnetic field develop?
- What is the interplay between magnetic fields, rotation and wind in the activity of stars, e.g. how does the angular momentum loss due to the magnetically-driven wind affect the dynamo of cool stars which in turn affects the wind?
- Under what conditions do OB stars become Be stars? What causes Luminous Blue Variable outbursts? What happens when a star reaches critical rotational velocity? What is the origin of γ Cas stars behavior?
- How does the solar cycle work? How is it influenced by the solar environment? What are the respective impacts of the global and small-scale solar dynamos?
- What explains the diversity of magnetic properties of M dwarfs? How is their magnetism related to that of planets, brown dwarfs and of solar-type stars?

Stellar evolution

- What is the role of magnetic field, rotation, metallicity and mass loss in the evolution of stars? In particular, how does it influence their late stages (white dwarfs, supernovae, neutron stars, black holes, γ-ray bursts)?
- What allows a fossil magnetic field to survive the various phases of stellar evolution?
- How strong was the solar magnetic field when the Sun was young? How will it evolve?

Stellar environment

- How does a stellar magnetic field influence mass loss, in particular what is responsible for wind clumping and the formation of a circumstellar disk or clouds?
- How do magnetospheric interactions impact binary stars? What are the tidal effects?
- How does the solar dynamo impacts our Earth, and how does it evolve with time?
- What are the star-planet magnetospheric interactions?

These questions will be answered by studying various types of stars: O stars which exhibit very strong clumpy winds, Of?p stars which have very specific spectral characteristic probably related to their magnetic field, active B stars which associate various extreme physical processes, Be stars which are very rapidly rotating and undergo outbursts producing a circumstellar disk, γ Cas stars which emit unexplained variable X-ray flux, Ap/Bp stars which host very strong fossil magnetic fields, A stars that are very weakly magnetized, δ Scu and γ Dor stars which pulsate, roAp stars in which magnetic field and pulsations interact strongly, Herbig Ae/Be stars which are the precursor of main sequence Ap/Bp stars, intermediate-mass T Tauri stars which cover the transition from a fully convective star to a radiative star, classical T Tauri stars which are still accreting mass, weak-lined T Tauri stars which have stopped accreting but have not yet reach the main sequence, solar-type stars with dynamo magnetic fields, young and old Suns to be compared with our Sun, cool supergiants which offer the possibility to study small-scale dynamos, M dwarfs which exist on both side of the full-convection threshold, red giants, planetary nebulae and post-AGB stars which represent later stages of stellar evolution, stars in the Magellanic Clouds which are in a different environment in terms of metallicity, and binaries which probe additional ingredients in stellar evolution and undergo tidal effects.

In addition to stellar physics, several additional science topics could be investigated with no or little changes in the proposed project. This includes for example studies of the ISM, white dwarfs, or novae. These examples are described in the more detailed document available on the UVMag website. Moreover, with some additional requirements, our project could be enhanced to also study other topics, e.g. exoplanetary magnetospheres. In this example, polarization signals of the order of 10^{-4} (for hot Jupiters) or less (down to 10^{-11} for Earth-like planets around solar-like stars) would be required, i.e. a very high signal-to-noise and very low instrumental polarization.

2.2 COR science objectives

Our science goals are well within the COR science objectives. In particular they would help understand how the first stars formed, evolved and influenced their environment, enriching it in various elements and leading to new generations of stars. They will therefore also allow us to pinpoint the mechanisms by which stars and their planetary systems form today. Finally, they will provide clues about how a stellar environment influences its planets and thus life on the planets.

3 Space mission

3.1 Concept

To observe in the UV domain, as well as to reach faint stars and weak magnetic fields, it is necessary to collect the requested observations from space. In addition, we wish to obtain long continuous spectropolarimetric time series of a number of targets, which is hampered from the ground when the variability period is close to 1 day or a fraction/multiple of 1 day. Finally, simultaneous spectropolarimetric observations in the UV and visible domains would provide information on the wind and polarization properties at the same time, providing new insights into certain phenomena such as magnetospheric confinement or chromospheric activity. We therefore propose to study a concept of a space spectropolarimeter working in the UV and visible domains. It could be installed either on a small space mission (small mirror, lower cost) dedicated to solving a limited number of stellar physics issues exposed above and available for long-term monitoring of stars, or on a large UV space observatory (LUVO) with which better statistics could be reached and where the spectropolarimeter could benefit other science topics besides stellar physics. However, more instrumental flexibility and complexity might then be needed, e.g. a MOS/IFU mode or an imaging mode.

Details about the instrumental concept can be found on the UVMag website and will be submitted to the forthcoming RFI #2.

3.2 Scientific requirements for the instrument

To measure the line profiles, we should obtain spectropolarimetric data with a high resolution. In addition, to fulfill our goals we need to reach a high signal-to-noise ratio and therefore to observe bright stars. We also wish to reach fainter stars to be able to observe certain rare classes of stars (such as M dwarfs or Herbig Ae/Be stars) and to probe other environments, e.g. the Magellanic Clouds. Thus our dynamical range needs to be very large.

Moreover, we would like to point in any direction in the sky, to reach any interesting target. We wish to observe once several thousands of stars of all types forming a statistical survey. We also require to be able to remain stably pointed on a shorter list of stars (targeted objects) continuously for 2 rotation cycles. Such time series document phenomena on stars that can be impulsive (flares, infall), periodic (pulsations, rotational migration of spots, corotating clouds), quasi-periodic (evolution of blobs from hot winds), and gradual (evolution of spots). While some hot stars rotate very fast (of the order of 1 day), other targets have rotation periods of several weeks. In Table 2 we considered that on average the rotation period is 2 weeks. The mission duration derives from this mean rotation period and the number of targets, at least 4 years. A mission of 12 years would not only allow to study 2 times more targeted and survey objects but to probe stellar magnetic cycles (similar to the 22-year solar cycle).

Table 2: Basic scientific specifications considered for the instrument. The minimal requirement is given, as well as the objective.

Specification	Requirement	Goal
Spectral range	117-320 + 390-870 nm	90-1000 nm
UV resolution	25000	100000 and 2000
Optical resolution	35000	80000
UV S/N	100	200
Optical S/N	100	300
Polarization	V in lines	QUV in lines + continuum
Instrumental polarization	3%	1%
Accuracy in radial velocity	1 km s^{-1}	0.3 km s^{-1}
Target magnitude	V=3-10	V=2-15
Targeted stars	50	100
Time per targeted star	4 weeks	6 weeks (4+1+1)
Survey stars	4000	8000
Time per survey star	20 min	30 min
Mission duration	4 years	12 years

Table 3: Number of available targets per spectral type, according to Simbad. An estimate of the number of magnetic stars is also given, according to the statistical occurrence of magnetic fields in each type of targets. Numbers are also given for some examples of rare types of objects. The numbers are given for the minimal requirement and goal for the magnitude.

Spectral type	V=3-10	V=2-15	Magnetic rate	Magnetic V=3-10	Magnetic V=2-15
O	428	1823	6%	26	109
B	19940	42891	6%	1196	2573
A	53143	102442	20%	10629	20488
F	61867	105487	50%	30934	52744
G	55780	97365	50%	27890	48683
K	88358	121052	50%	44179	60526
M	10276	18367	50%	5138	9184
Be stars	1225	1705	1%	12	17
Herbig Ae/Be	44	60	10%	4	6
M dwarfs	94	693	50%	47	347

Precise radial velocity is requested for example for Doppler Imaging of active binary systems or probing the redshifts of high temperature emission lines in the subcoronal atmospheres of cool stars.

Polarization in Stokes V in spectral lines is the minimum requirement to be able to infer magnetic properties. However, polarization in QUV would allow full 3D mapping of the magnetospheres and linear polarization (QU) would also allow to measure other physical processes such as depolarization from a circumstellar disk, probing scales well beyond what is feasible with interferometry. In addition, polarization of the continuum would be very useful to study dusty environments, providing important information about e.g. star forming regions or protostars.

3.3 Ongoing activities

Previous UV instruments (e.g. IUE, STIS or FUSE), have provided valuable data for the first studies of stellar magnetospheres. HIRDES on the future WSO would also provide the instrumental capabilities needed to address the scientific rationale exposed here. However, these instruments are either unavailable anymore or available for too short periods of time to perform a time series over a full stellar rotation cycle. This is why we need a new UV spectrograph.

In addition, ground-based optical spectropolarimeters provide important datasets for all types of bright stars. However, there are no space stellar spectropolarimeters, to reach fainter targets and to obtain continuous timeseries. Moreover, UV spectropolarimetry cannot be achieved from the ground. There are already several ongoing projects in this field in the optical (e.g. for SST, Solar Orbiter or SPEX), but not in the UV. However, in the frame of UVMag, a Research & Technology (R&T) study funded by the French space agency CNES has just started at IRAP and LESIA, to develop a prototype of a space-based spectropolarimeter. Space-based spectropolarimetry is very novel, especially in the UV, but we expect that the required technology will be available by the time a mission would be launched.

Response to Request for Information: NNH12ZDA008L
Science Objectives and Requirements for the next NASA UV/Visible Astrophysics Mission Concepts

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This response to the RFI will emphasize the importance of times series studies and polarimetric capability for future NASA missions.

My own area of research concerns the general topic of stars, especially stellar winds and circumstellar disks, and have included objects such as the Wolf-Rayet stars, Luminous Blue Variables, O stars, Be stars, magnetic massive stars, and evolved cool giants and supergiants. I have been involved with multiwavelength studies of these objects, ranging from the X-ray band to the radio. I have been involved with awards of observing time that include Chandra, XMM-Newton, Suzaku, RXTE, FUSE, Spitzer, and ISO. (Ground-based efforts include data acquired with ESO's VLT, the CFHT, and the EVLA.)

Although the arena of theoretical and interpretive modeling is my primary focus, I am certainly involved in obtaining new data (as PI or co-I) and making use of archival data. As such, I have a vested interest in the strength of NASA's future plans for space-borne telescopes and associated funding programs.

In my, admittedly, narrow subdiscipline of circumstellar studies, the issue of "structure" in winds and disks has become of central importance of late. The clumping aspects of stellar winds has proven to be critical for obtaining better mass loss rates of massive stars, with consequences for understanding both stellar and galactic evolution. Magnetism of massive stars has matured greatly as a subfield. Detections are now regularly reported, and there have been significant successes from theory in explaining a number of phenomena associated with rotating magnetospheres and stellar winds (although it is clear that there is much work remaining).

Although the ability to obtain spectral energy distributions or high quality line profiles are and will continue to be important, another "style" of observing that has proven to be of immense scientific value and highly productive has been time series studies. A few examples would include:

- The Kepler and COROT missions for finding exoplanets along with the added benefit of variability studies (e.g., non-radial pulsations of B stars).
- Variability studies by the RXTE that have proven critical for our understanding of compact objects.

- CFHT and VLT studies of massive star magnetism. Although the presence of magnetism is achievable with a single detection of the Zeeman effect, characterizing the magnetic field strength and dipole orientation requires multiple spectra within a rotational phase.

The end result is that variability studies have been a mainstay of astronomical scientific investigation. No one contests this. Yet, my experience with proposing to programs such as Chandra, Spitzer, and others is the all-too-familiar threat that time-constrained observations will be frowned upon.

I understand that with advances in capability, there is much to be gained by looking at the most diverse set of sources possible. I also appreciate the challenges associated with efficient use of instrumentation when time-constrained observations are involved. However, we are now in the post-Great-Observatories era. (Yes, 3 of the 4 continue to operate, but this RFI is looking to the future.) As such, and being a researcher who straddles the line between theory and observing, I would like to emphasize the importance of having a program that encourages time series studies, especially in conjunction with reasonably high spectral resolution capability at UV and visible wavelengths. Such capability will prove crucial for addressing outstanding questions about stochastic (e.g., clumping) and ordered (e.g., corotating interaction regions, or "CIRs") structures in massive star winds, and shock physics in supersonic flows arising from physical instabilities, colliding winds in binary systems, or magnetically channeled flow. Similar considerations apply to other classes of stars, ranging from AGB types to young forming stars.

In addition to an emphasis given to time series studies, I also wish to advocate for polarimetric capability. I was the lead organizer for a conference entitled "Stellar Polarimetry: From Birth to Death" that was held in summer 2011 (proceedings now in print under Hoffman et al., 2012, AIP Conf. Proc.). That meeting certainly demonstrated the importance of photopolarimetry, spectropolarimetry, and imaging polarimetry for advancing our understanding of stellar astrophysics, ranging from forming stars through supernova and compact objects.

Unfortunately, polarization is a somewhat underutilized tool in astrophysical inquiry. There are some ground based facilities with polarimetric modes of operation. However, few NASA missions have included polarimetric instrumentation. WUPPE and WISP were small missions with a focus on UV polarimetry, but they have certainly been among the very few.

There is no doubt that polarimetric capability adds complexity to the instrument design, the reduction pipeline, and observing planning. Polarimetric capability also adds important new diagnostics for astrophysical inquiry, as evidenced for example by the NASA GEMS mission. Polarization can immediately reveal whether an unresolved source is essentially spherically symmetric or not. Using the Zeeman effect, circularly polarized lines are used to detect stellar magnetism. Time series studies of polarized radiation from stellar sources trace the time varying geometry of sources. Senstive to scattering and absorptive properties, polarization has long been important for interstellar studies and for understanding dust grains. Polarimetric data are important for studies of jets for AGN, for example because of polarized synchrotron emission. Faraday rotation is important to studies of interstellar magnetism. Polarization could also one day prove to be key in studies of exoplanets. And of course polarization has recently been prominent in cosmological studies of the cosmic background radiation.

NASA has been successful in pushing to make as many wavebands accessible for astronomical study as possible. Often, the goal is to go fainter (generally accompanied by better spatial resolution), which usually means being able to detect things that are either more distant, less luminous, or having lower surface brightness. The inclusion of polarimetric capability is less about opening a new waveband than of providing new leverage on old wavebands through the powerful diagnostics of linear and circular polarization. I simply want to make the point that the quest to go fainter is not the only way to advance the astrophysical sciences, and that polarimetry has broad appeal to the astrophysical community.

A Science Whitepaper submitted in response to the 2012 COR RFI for UV/Optical Science Investigations

Mass Transport Processes and their Roles in the Formation, Structure, and Evolution of Stars and Stellar Systems

10 August 2012

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Introduction

Understanding the formation, structure, and evolution of stars and stellar systems remains one of the most basic pursuits of astronomical science, and is a prerequisite to obtaining an understanding of the Universe as a whole. The evolution of structure and transport of matter within, from, and between stars are controlled by dynamic processes, such as variable magnetic fields, accretion, convection, shocks, pulsations, and winds. Future long-baseline (0.5-1.0 km) observatories (i.e., space-based interferometers and sparse aperture telescopes) will achieve resolutions of 0.1 milli-arcsec (mas), a gain in spatial resolution comparable to the leap from Galileo to HST. As a result, spectral imaging observations from such facilities will enable a quantum leap in our understanding of stars and stellar systems. In this whitepaper, we discuss the compelling new scientific opportunities for understanding the formation, structure, and evolution of stars and stellar systems that can be enabled by dramatic increases in UV-Optical angular resolution to the sub-mas level. An Ultraviolet-Optical Interferometer (UVOI) with apertures on that order would provide direct spectral imaging of spatial structures and dynamical processes in the various stages of stellar evolution (e.g., Fig. 1) for a broad range of stellar types.

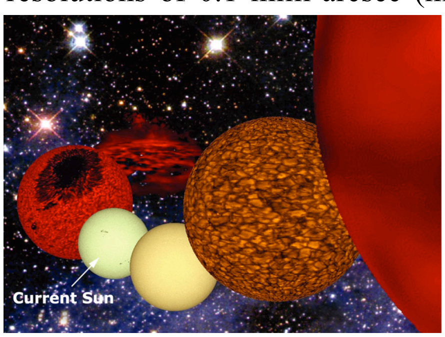

Fig. 1: Evolution of the Sun in time.

We discuss below the opportunities available for dramatically improved observation and understanding of: young stellar systems; hot star rotation, disks, & winds; stellar pulsation across the HR-diagram and its impact on stellar structure and mass loss; convection in cool, evolved giant and supergiant stars; interacting binaries; novae and supernovae. Hours to weeks between successive images (see Fig. 2) will detect dramatic changes in many objects, e.g., mass transfer in binaries, pulsation-driven surface brightness variation and convective cell structure in giants and supergiants, jet formation and propagation and the changes in debris disks/shells in young planetary systems due to orbiting resonances and planets, non-radial pulsations in and winds from stars, and the structure, evolution, and interaction with the ISM of the core regions of nearby supernovae.

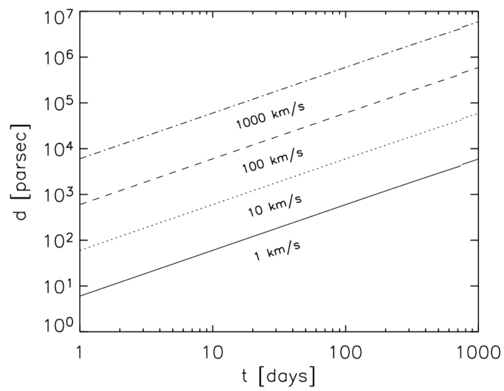

Fig. 2: Minimum time interval between successive images required to resolve the motion of a feature moving at different speeds, as a function of the object's distance.

Relevance to Top-Level COR Science Objectives

The science investigations described herein address several of the high-level COR science objectives, including: "how did we get here?", "what are the mechanisms by which stars and their planetary systems form?", "how are the chemical elements distributed in galaxies?", and the later stages of the question "how does baryonic matter flow form the intergalactic medium to galaxies and ultimately into planets?" This whitepaper also responds to the RFI request that respondents "*attempt to imagine compelling scientific investigations in an era well beyond the present*" to support the synthesis of a "*wide range of far-reaching ideas*", goals readily met by investigations requiring the ultra-high angular resolution described in this whitepaper. The lead author of this paper is willing to participate and present this material in a COR workshop, if invited.

Dynamic Processes in Young Stellar Systems: Star Formation, Protoplanetary Disks and Jets

Protoplanetary disks are where the materials that can ultimately produce life-bearing worlds are assembled. For our own Solar System, the first 50 Myr spans the formation and evolution of the proto-Solar nebula, the assembly of the meteorite parent bodies, the formation of the proto-Earth and proto-Mars, and the early phases of the Era of Heavy Bombardment. *If we are to understand not only the history of our Solar System, but also how planetary systems develop in general, we need to understand the disks, how long they last, how they interact with their central stars, and how they evolve.*

For the first few million years, both young solar type (T Tauri) and intermediate-mass (Herbig Ae) stars continue to accrete material from their disks. The inner boundaries of these disks are expected to be at the co-rotation radius from the star, typically 3-5 stellar radii (~0.05 AU for the T Tauri stars). The environment closer to the star is controlled by the strong stellar magnetic field, with accreting material channeled along field lines to the stellar photosphere. In the accretion shock plasma temperatures increase from several thousand to a few million degrees. Due to the high temperatures, UV emission from the chromosphere and the accretion spot(s) is detectable at high contrast against the lower-temperature stellar photosphere. While inner disk edges have been resolved by HST for dust disk cavities with radii in the 10-20 AU range[7], the inner edge of the gas disk has yet to be resolved for any young star with HST, but would be resolved with a UVOI for stars as distant as 160 pc. Fig. 3 shows a simulation of

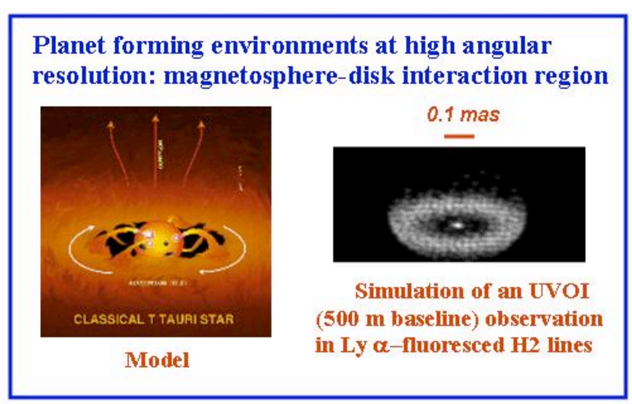

Fig. 3: A simulation of a sub-mas observation of the Lyα-fluoresced H2 emission originating in the magnetosphere-disk interaction region of a T Tauri star at ~50 pc.

such an observation of the Lyα-fluoresced H_2 emission originating in the magnetosphere-disk interaction region of a T Tauri star at ~50 pc. Determining the size and geometry of the field-dominated region is of great importance for understanding stellar rotational braking, and accretion rates[3] as a function of global disk parameters. In addition to providing the size of the region, repeated observations may reveal rotation of resonances and indirectly point to the location of planets. Moreover, direct detection of planets associated with young, active stars may be possible via their UV auroral emissions or via transits and the impact of close-in exoplanets on the activity of their hosts stars may be evaluated.

Red-shifted absorption features in T Tauri star spectra[5] and lack of X-ray eclipses[8] has been interpreted as indicating that the accretion footprints on young stars are at high stellar latitudes. Sub-mas spatial resolution will allow us to directly image the accretion hot spot(s), and provide a map of the accretion flow from the co-rotation radius of the disk onto the accretion footprints, using emission lines spanning a wide ionization range. Such imagery will allow us to test how the accretion geometry changes with stellar mass, age, and disk properties.

Dynamic Processes in Hot stars: Rotation, Disks, Winds, and Circumstellar Envelopes

There are many competing processes on stars that produce structures on the surface or in the circumstellar environment. These processes include radiative winds, rapid rotation, pulsations, and magnetic fields, many of which may operate simultaneously within the stellar envelope.

Understanding how massive stars rotate is important for the accurate modeling of stellar evolution and computing the final chemical yields of stars[11]. Hot (O, B, Wolf-Rayet) stars tend to be the most rapidly rotating types of stars (excluding degenerate stars), and many are rotating so fast that their shapes are centrifugally distorted into oblate spheroids. Although rapid rotation in the very rare eclipsing binaries is measurable using light curves and radial velocity profiles, it is extremely difficult to pin down the detailed properties of single-star rapid rotation. A UVOI would enable direct measurement of the rotation rate and any differential rotation by imaging features moving across the star at different latitudes. Imaging the stellar oblateness will provide a better measure of the star's total angular momentum than feature-tracking alone could provide.

Hot stars exhibit strong stellar winds that contribute significantly to the mass and energy balance of the interstellar medium. Quantitative modeling of UV spectral features associated with stellar winds has evolved into a reasonably accurate means of deriving fundamental stellar parameters and distances[10]. The atmospheres and winds of hot stars are intrinsically variable, and it is now accepted that in many cases time-dependent phenomena (e.g., pulsations or magnetic field evolution) in the photosphere provide "shape and structure" to the wind[6]. The direct observational confirmation of a causal connection between specific stellar variations and specific wind variations, though, has proved elusive. For many O and B stars, it is not clear whether large-scale wind inhomogeneities are rotationally modulated (i.e., due to spots) or if pulsations are responsible, or if the variability occurs spontaneously in the wind. Sub-mas observations would shed light on the origins of wind variability. Simply seeing correlations between individual spots (no matter their physical origin) and modulations in the wind would be key to understanding how hot stars affect their local environments. One paradigm to be tested is the idea that discrete absorption components (DACs) are caused by corotating interaction regions (CIRs) in the winds[4]. While continuum-bandpass filters can be used efficiently to search for thermal and diffusive inhomogeneities on a hot star’s disk, most other processes are best studied by imaging in UV spectral lines. From the ground one can do some imaging in Hα, but it is so optically thick that structures are hard to see. In the UV, however, the CIV doublet can be employed to study inner winds and co-orbiting structures of hot stars, while the MgII doublet can be used to trace the discrete ejections of mass and the extent of disks out to several stellar radii.

Pulsation Processes and their Impact on Stellar Structure and Mass Loss

Pulsations are found in many different types of stars, ranging from very hot main-sequence stars to dying cool giants and supergiants, and stellar relics. *In many cases stellar pulsations, radial or non-radial, significantly affect the extent, composition, and structure of stellar atmospheres*. The signatures of pulsation are very prominent in the UV (e.g. Mg h&k lines) and a UVOI will enable direct imaging of pulsation effects including surface structures and shock fronts as they propagate through the dynamical atmospheres. Images of the effects of the pulsation will provide key inputs to hydrodynamical models for a range of diverse pulsators, such as Miras and Cepheids, cool supergiants, and hot B-stars. Direct observation of the shock-propagation in extended stellar atmospheres and winds will characterize the time evolution and spatial symmetries of shocks and constrain and improve theoretical shock models in stars with a wide range of masses. *These observations will answer a large number of crucial questions about stellar interiors, core convection, chemical mixing, and magnetic fields.*

Nonradial pulsations (NRP's) produce evenly spaced temperature modulations that can be imaged as bright and dark zones on the star. Surface thermal modulations may amplify wind flows into clumps. The ultimate tests of both interior pulsation theory and line profile models will be the counting of the hot/cool zone pairs on the star and the determination of whether they only are concentrated on a star's equator. Theories of NRPs, e.g., in very rapidly rotating stars, are still evolving, and the imaging of how rotation affects the latitudinal profile of pulsation amplitudes would verify or falsify certain modeling assumptions and directly diagnose the angular momentum profiles of these stars[17]. *For example, the direct imaging of a cause-and-effect relationship between stellar and circumstellar features could provide the long-sought explanation for the Be phenomenon*.

Convection in Cool Evolved Giant and Supergiant Stars

Stars that are at least 1.5x heavier than the Sun are not magnetically active during their mature life on the main sequence because they lack envelope convection. Consequently, they begin their transformation to red giant stars with essentially the same rotational energy they had after their initial formative epochs. As they expand, a dynamo is activated once the star cools enough to develop envelope convection. That may lead to significant, sudden magnetic braking, which possibly results in a substantial difference between the rotation rates of the deep interior and the magnetically-active convective envelope[16]. Observations indicate that such a difference may last for up to some tens of millions of years. Detailed understanding of the onset of dynamos in evolving stars with such shear layers between envelope and interior, and of the possible consequences for the internal dynamics, will greatly benefit from imaging and disk-resolved seismic observations of stars in such evolutionary phases.

Continuing their evolution as red giants, the stars reach a point where the coronal activity disappears again, to be replaced by substantial mass loss at much lower temperatures. In a HR-diagram this behavior occurs on either side of a dividing line. Even though there is an absence of magnetically heated transition-region and coronal plasma in the late-K and M-type giant stars, their winds are thought to be driven by magneto-hydrodynamic waves. It has been proposed[15] that the coronal dividing line is a consequence of a dynamo transition: large-scale structures with closed field lines and coronal heating, and small-scale structures with open field lines and increased mass loss. The hybrid stars that display both phenomena are the key to understanding the dividing line and the associated change in the dynamo mode from global to local. Sub-mas imaging of the transition-region and chromospheric emissions in the UV will reveal the magnetic field topology on stars on both sides of the dividing line, and on the hybrid-atmosphere stars.

As stars expand to supergiant stages, the scale of the surface convection changes to the point that we expect only a few convective 'granules' to cover the entire star. Fig. 4 shows a model and simulated sub-mas observation of this convection. Does this really happen? Some doubt it because the spectral lines of these stars show little sign of such large-scale turbulence. And if it does, then a turbulent local dynamo may again create magnetic fields on a near-global scale. A UVOI can image both the large-scale convection (and its evolution) and possible chromospheric patterns driven by this process.

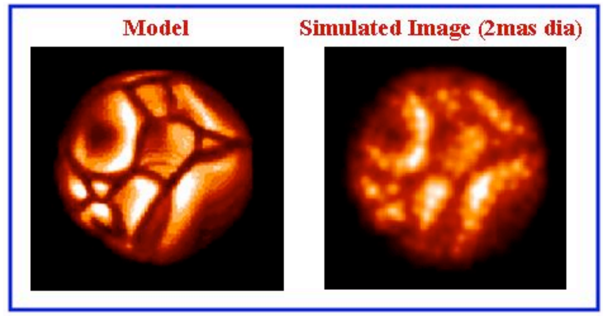

Fig. 4: Model (B. Freytag) and simulated observation (500m baseline) of the convection on a supergiant like α Ori at 2 kpc. These "granules" transport the energy from the interior to the surface, evolving on a timescale of years, with ~dozen granules filling the entire surface.

Interacting Binary Systems: Understanding Accretion Processes

Almost all high-energy sources in the Universe are powered by potential energy released via accretion. Understanding accretion driven flows in binaries will directly affect our understanding of similar flows around YSOs, including the formation of planets in the circumstellar disk, as well as the much larger scale accretion flows in active galactic nuclei (AGNs). Compact, mass transferring binaries provide us with laboratories for testing energetic processes such as magnetically driven accretion and accretion geometries, and various evolutionary scenarios.

In close binary stars the flow of material from one component into the potential well of the other determines the future evolutionary histories of each component and the system itself, and particularly the production of degenerate companions and supernovae. Our cosmological standard candles, the Type Ia supernovae, for example, may be a consequence of accretion onto a white dwarf in a close binary. Currently, most of our accretion paradigms are based on time-resolved spectroscopic observations. For example, in Cataclysmic Variables (CVs) the picture of accretion onto compact objects via an extended accretion disc is solidly based on spectral and timing information. However, several objects challenge our standard picture and there are significant gaps in our understanding of their formation and evolution.

One key to further advances in accretion studies is resolving a wide range of interacting binaries and studying their components and mass flows. Sub-mas resolution in the UV will lead to unprecedented opportunities for detailed studies of accretion phenomena in many interacting systems, including symbiotics[9], Algol-type binaries (Fig 5), and CVs[12]. A UVOI will be able to resolve the components of numerous interacting systems and provide a unique laboratory for studying accretion processes and jet-forming regions. The binary components can be studied individually at many wavelengths including Lyα, NV, CIV, and MgII h&k lines, and the geometry of accretion, including high temperature regions, hot accretion spots[13], bipolar flows and jets, and can

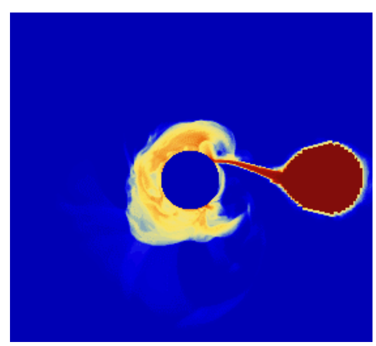

Fig. 5: Hydrodynamic simulations[14] of the mass transfer in the Algol prototype β Per (2 mas separation), showing H-alpha emissivity. The gas stream impacts onto the surface of the primary forming a local hotspot as well as an extended flow around the accretor.

be imaged directly, giving us the first direct constraints on the accretion geometries. This in turn will allow us to benchmark crucial accretion paradigms that affect any stellar population and even the structural evolution of galaxies whose central black-holes are steadily accreting, shaping their long term evolution.

Supernovae and Novae

With the exception of the relatively nearby SN1987A (in the LMC), which could be well-studied by HST, it has not been possible to obtain much information about the close-in spatial structure of supernovae (typical sizes remain below about 1 mas, which is not reached by current ground-based optical telescopes). Radio VLBI observations have resolved a few supernovae, but are more a probe of the interaction of the SN shock front with the circumstellar material than of the supernova[1]. Direct imaging at the sub-mas level would resolve early stages of expansion of supernovae at a distance of few Mpc, and of galactic novae. These images would provide essential information on the nature of the explosion, especially in regard to its symmetry or asymmetry, and of the early evolution of its structure with time.

Conclusion

We have summarized some of the compelling new scientific opportunities for understanding stars and stellar systems that can be enabled by sub-mas angular resolution, UV/Optical spectral imaging observations, which can reveal the details of the many dynamic processes (e.g., variable magnetic fields, accretion, convection, shocks, pulsations, winds, and jets) that affect their formation, structure, and evolution. These observations can only be provided by long-baseline interferometers or sparse aperture telescopes in space, since the aperture diameters required are in excess of 500 m and since they require observations at wavelengths (UV) not accessible from the ground. Such observations would enable tremendous gains in our understanding of the individual stars and stellar systems that are the building blocks of our Universe and which serve as the hosts for life throughout the Cosmos.

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Understanding Global Galactic Star Formation

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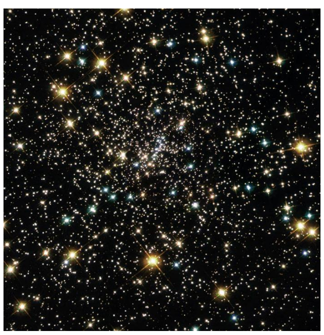
Science RFI Response to NASA Cosmic Origins Program

Abstract

We propose to the community a comprehensive UV/optical/NIR imaging survey of Galactic star formation regions to probe all aspects of the star formation process, a listed key question in the Cosmic Origins science goals: **what are the mechanisms by which stars and their planetary systems form**? The primary goal of such a study is to understand the evolution of circumstellar protoplanetary disks and other detailed aspects of star formation in a wide variety of different environments. This goal requires a comprehensive emission-line survey of nearby star-forming regions in the Milky Way, where a high spatial resolution telescope+camera will be capable of resolving circumstellar material and shock structures. In addition to resolving circumstellar disks themselves, such observations will study shocks in the jets and outflows from young stars, which are probes of accretion in the youngest protoplanetary disks still embedded in their surrounding molecular clouds. These data will allow the measurement of proper motions for a large sample of stars and jets/shocks in massive star-forming regions for the first time, opening a new window to study the dynamics of these environments. It will require better than 30 mas resolution and a stable PSF to conduct precision astrometry and photometry of stars and nebulae. Such data will allow production of precise color-color and color-magnitude diagrams for millions of young stars to study their evolutionary states, while also providing stellar rotation, multiplicity, and clustering statistics as functions of environment and location in the Galaxy. For the first time, one would be able to systematically map the detailed excitation structure of HII regions, stellar winds, supernova remnants, and supershells/superbubbles. This survey will provide the basic data required to understand star formation as a fundamental astrophysical process that controls the evolution of the baryonic contents of the Universe.

Introduction & Scientific Context



Stars are the fundamental building blocks of the Universe and influence its evolution on all scales, from the cosmological to the planetary. The formation of stars locks away baryons for a Hubble time, they produce the energy that establishes the state of matter in the interstellar medium (ISM), they control the fate of self-gravitating masses, and they produce the light that renders distant galaxies visible. It is because of stars that elements heavier than helium are created. Without stars, there would be no planets, no carbon, and no free energy to drive the evolution of life. Star formation is *the* fundamental process underpinning the evolution of the Universe and life within it. Progress toward understanding the cosmic history of normal matter, the formation and evolution of galaxies, the birth and fate of planetary systems, and our own origins requires a comprehensive understanding of star formation *as a large-scale, coherent, systematic process.*

There has been remarkable progress in our understanding of star formation during recent decades. Molecular clouds form from the ISM. Their densest cores suffer gravitational collapse to form protostars, which are 107 times smaller, and 21 orders of magnitude denser. Spin and pressure gradients channel accretion from the envelope onto a spinning disk. Magnetic fields grow, extract angular momentum, and drive accretion from the disk onto the star. Dynamo-generated stellar magnetic fields regulate stellar rotation, accrete matter onto the star at high latitudes, and expel supersonic jets and bipolar outflows. Particles in the disk grow, coagulate, and eventually form planets around the young star.

Observations, theory and numerical simulations have led to major paradigm shifts in this simple description of star and planet formation. First, the birth of isolated stars from a quiescent dark cloud is rare. Observations have shown that most stars form in turbulent giant molecular clouds with supersonic motions having Mach numbers of 10 to 100. Second, most stars form in dense clusters in close proximity to tens, hundreds, or even thousands of other stars. Some siblings are massive stars with powerful stellar winds, intense UV radiation fields, and violent and explosive deaths that dramatically affect the surrounding ISM. The vast majority of normal stars, probably including our own Sun, formed in such OB associations. Feedback of light, energy, and matter drives and regulates cloud formation, gravitational collapse, and the properties of the individual stars, multiple systems, and the clusters that form. These stochastic turbulent processes appear to be fundamental to understanding the origin and distribution of stellar masses and other stellar properties.

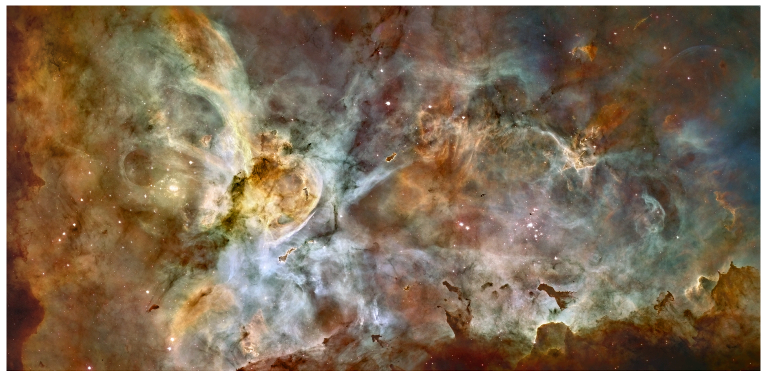
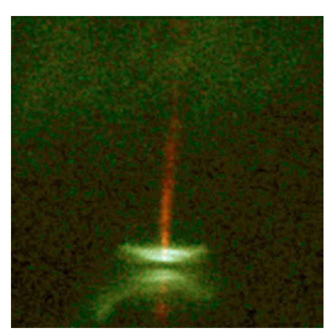


Figure 1 – the HST mosaic of the Carina Nebula (Smith et al 2008). This is the kind of dataset that, when replicated across all massive star forming regions within 2-2.5 kpc of the Sun, will yield a dataset capable of unlocking the secrets of star formation as a global process

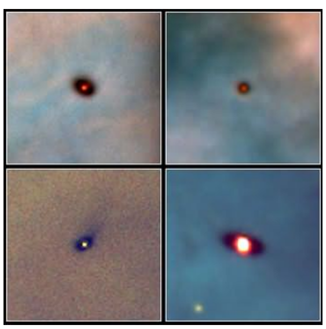
Compelling Science Themes Based on Recent Advances

We believe that to understand and address star formation as a global *system*, we need to design and engage in a systematic program of imaging that covers a large number and variety of Galactic star forming regions. To understand star birth in the early Universe, to understand galaxy formation and evolution, to understand the origin of the stellar mass spectrum, to understand the formation of planets, and to understand feedback, we must treat star birth as an integrated systemic process. We must observe star forming complexes in their entirety: we must trace the interactions between gas and stars, between stars and stars, and between disks and their environments. To make progress, we must spatially resolve disks, multiple stars, and star clusters. We must measure stellar motions, and perform relative photometry with sufficient precision to age-date young stars. All these top-level goals make specific requirements of any instrumentation designed to execute this program – requirements that we will detail in subsequent sections. At the heart of this program is the goal of providing critical advances in our knowledge of star and planet birth.



The goals of our Galactic star forming imaging program are to make major advances in the following topics:

Young stellar Objects (YSOs): *Masses, mass-spectra, rotation rates, variability, ages, multiplicity, clustering statistics, motions, brown dwarfs, free-floating proto-planets*. We need to be able to trace individual star, multiple star, and cluster properties to assay the range of star formation products and the manner in which they are assembled – a goal that requires the combination of a wide field of view, high angular resolution, and photometric and astrometric stability potentially enabling sub-mas relative astrometry, and milli-mag relative photometry. Measurement of the orbital motions of stars is necessary to gain insight into the dynamics of stars once they are produced, how cluster dispersion varies, and the possible detection of high velocity stars, as well as mapping large-scale nebular motions. Such measurements all require 1 km/s proper motion sensitivity for both stars and compact nebulae. Measurement of the stellar rotation rates for most stars is necessary to understand the resulting dynamics of each star formation episode and is achieved by recording star-spot modulation using precise relative photometry. Of particular interest is the search for transiting proto-planets in a subset of edge-on disks, and with a large-area imaging survey we will capture extremely rare types of events such as proto-planet collisions in 1 to 100 Myr old debris disks in associations. Precise cluster and association ages will be determined by fitting of HR diagram turn-on and turn-off loci requiring accurate relative photometry. Extending this same photometry to binaries will enable the best calibrations of pre-main sequence evolutionary tracks. Addressing the questions of clustering, young cluster evolution, and cluster dissipation will require stellar positions and motions to be probed. With such datasets we will identify many young brown-dwarfs and free-floating protoplanets.



Disks: *Sizes, masses, structure, mass-loss rates, photo-evaporation, density distributions, survival times*. A primary goal is to identify thousands of protoplanetary disks seen in silhouette, and embedded within evaporating proplyd envelopes in dozens of nearby HII regions, out to a distance of about 2 kpc. The widefield survey images taken toward regions such as Orion or Carina will extend the surveyed areas by one to two orders of magnitude over the most ambitious HST surveys undertaken so far. It will be possible to sample disks with ages ranging from 0.1 Myr to over 100 Myr when a variety of selected lines of sight are observed toward the Perseus, Orion, and Carina regions. It will be possible to look for spiral structure, gaps, and other evidence of disk perturbations from both internal and external influences. The nearest disks are 50 pc from the Sun toward TW Hya, Sco-Cen, and Perseus. We believe we will need to approach an angular resolution of nearly 1 AU at the shortest wavelengths toward these systems (20 mas at $\lambda \approx 0.2$ μm). Hα and other key spectral line-diagnostics will be used to estimate photo-ionization induced mass-loss rates in irradiated proplyds, giving critical clues to their typical lifetimes.

Outflows: *Microjets, jets, wide-angle flows, winds, motions, momenta, mass-loss rates, turbulence, shocks*. HST has demonstrated that 0.05″ imaging is needed to begin to resolve the structure of shocks, and distinguish shock fronts from post-shock cooling layers. Furthermore, only space-based UV/optical observations can measure proper motions on a time-scale short compared to the cooling time. The survey observations will measure the proper motions of hundreds of outflows, enabling the first direct measure of the momentum and energy injected into the ISM by protostellar outflows for a wide-range of stellar masses and star forming environments. Jet orientation changes will trace the history of stellar encounters in clusters. We will also measure the angular momentum of jets to determine their launch points. While jets and shocks are interesting in their own right, as they emerge from a molecular cloud they also provide a signpost of the youngest protoplanetary accretion disks that are still deeply embedded. The spacing of major ejecta within a single outflow system traces the accretion history of the source YSO. In this way, jet structure provides a fossil record of the accretion and mass-loss histories of the source stars.

Nebulae: *Excitation, motion, ionization fronts, triggered star formation*. Star formation disrupts molecular clouds with ionization fronts, champagne flows, and PDRs - much of this activity will suppress continued star formation, while some appears to trigger it. Observations of these processes across a wide parameter space are needed to compare with theoretical simulations that are now available. High spatial-resolution images with multiple narrowband filters are essential to resolve and map the nebular ionization structure, which reveals the optical depth to the Lyman continuum and radiative feedback that drives the PDR. Each HII region / OB association provides a snapshot in time of a range of evolutionary stages. The portions of each region closest to the massive stars are likely to be the most evolved and oldest parts of each region. As one moves away from the center, the gas, stars, and disks are likely to be in a younger evolutionary state.

Massive stars: *Motions, variations, winds, interactions with siblings, HII regions*. The program will also investigate stellar wind bubbles in HII regions and the interactions of stellar winds with cometary clouds, proplyds, naked young stars and their winds and jets, and the surrounding ISM. Another goal will be to investigate the properties of C-symmetric jets and outflows, wind-jet interactions, supernova-protostellar jet interactions in Orion, Carina, Rosette, NGC 3576, and other regions.

Recycling: *Supernova remnants and planetary nebulae, bulk motions, excitation, shocks*. The late stages of stellar evolution - especially in massive stars - are an integral piece of the star and planet formation puzzle, because outflows from the deaths of massive stars drive the chemical evolution and energetics of the ISM. In particular, supernova ejecta enrich the ISM with the elements needed for life to exist, while supernova shocks and stellar winds may compress the surrounding ISM to trigger new star formation. Outflows from the deaths of intermediate mass stars (planetary nebulae) also enrich the ISM with dust, which is vital to the formation of molecular clouds. By studying the structure and proper motions of a representative sample of nearby supernova remnants (the Crab, IC443, Cas A, Vela, the Cygnus Loop, etc), WR star bubbles (NGC6888, NGC2359), and planetary nebulae (the Helix, M27, etc.), the fine details of the shocks and ionization fronts can be spatially resolved. The supernova remnants IC443 and Vela are particularly

interesting, as they are directly interacting with molecular clouds. Also, this survey will probe unique regions such as Carina and NGC3603, where the stars are so massive and their lifetimes so short that their imminent death (Eta Carinae and Sher 25) is directly affecting the birth of stars in the same region. Altogether, these data will probe the disruption of clouds, the recycling of stellar ejecta, and the compression of the ISM into new generation of clouds and the triggering and propagation of star formation.

Superbubbles: *Destruction of clouds, OB associations, T associations, global structure and evolution of star forming regions*. The energy input from the combined influence of UV radiation, stellar winds, and supernovae from massive stars makes "swiss cheese" out of the ISM. In the most massive star forming regions, where dozens of OB stars live fast and die young before moving very far from their birth sites, the combined effect of this feedback can blow giant shells or "superbubbles" that may eventually break out of the galactic plane, driving a galactic fountain that is vital to the recycling of the ISM. In a few regions such as Carina, NGC3603, NGC3576, W1, and W4, we have the opportunity to study the formation of superbubbles in exquisite detail, where we can actually resolve the structure of the expanding bubbles and model their physical properties.

The Galactic Ecology: *Impact of spiral arms, formation of clouds, Galactic gradients in YSO and cluster properties, the Galactic Center*. We believe an investigation of the "galactic ecology" is vital to understanding the global nature of the star formation process - the formation of giant molecular clouds from the ISM. How do HII regions and superbubble ionization fronts compress the surrounding ISM? Does ram-pressure trigger cloud formation? How do spiral arms trigger cloud formation? How do clouds and cloud cores collapse into clusters, and multiple stars?

Broad Design Specifications Driven by this Science

To achieve the science goals of this program a variety of capabilities need to be implemented. The majority of the tracers and the various phases of the ISM and stellar populations being targeted require the angular resolution and wavelength agility of a medium to large aperture (1.5-4m) UV/optical space telescope combined with a wide-field imaging camera that can provide diffraction-limited images into the UV-blue to capture the UV-bright stellar populations that HST has only been able to recently reach with the installation of WFC3/UVIS. Such a telescope needs to be located in an orbit that is both dynamically and thermally stable (such as L2) to produce the photometric stability required by many aspects of the science goals. A broad complement of both broad- and narrow-band filters will be necessary to isolate and measure not only the unique tracers of specific atomic species but also the trends in stellar color across entire swaths of our local Galactic neighborhood.

While the science program in this paper have defined a loose set of specifications (see Table 1), it should be recognized that the opportunity for truly unique discovery is made possible by the **combination** of both a wide angular field of view (tens of arcminutes on a side) **with** the diffraction limit of a medium to large aperture in the UV/optical (resolution elements below 10-20 mas). HST and JWST have provided and will provide exquisite resolution but can efficiently survey only over very small fields of view. Many problems require not only large collecting area and high resolution, but also large fields of view to locate and characterize rare objects, or suites of objects, whose location cannot be known a priori.

Four Central Questions to be Addressed

1. What is the formation and survival rate of Solar System class objects in massive star forming regions? There is a growing body of evidence that many stars form in these environments, and that our own Sun was one such system, based on meteoritic evidence concerning ^{60}Fe.
2. What is the role of triggering and feedback in star formation propagation? A wide range of predictions from numerical simulations describe the role of triggering and feedback as being anything from dominant to negligible. What is the correlation between environment and the nature of the stellar population that forms in secondary and even tertiary star formation events?
3. How is the distribution of star formation across a galactic disk managed? We see evidence that an increase in the efficiency or intensity of star formation occurs almost simultaneously across large distances – what is the source of these global modes – what environmental changes are necessary to initiate and support star formation at these levels?
4. When considering global star formation, what are the determining factors that cause stars to form in one place as opposed to another? At the microphysics level, how does elevated or starburst star formation compare to the more common modes? What dictates the intrinsic efficiency of the star formation process? These latter questions will require comparison with observations from other nearby galaxies such as the LMC, but the database of observations from this program will be necessary to lay the groundwork to answer them.

Parameter	Specification	Justification
Field of View	At least 200 sq. arcmin	To allow a statistically complete survey of as many targets and environments as possible in a reasonable period of time
Resolution	Diffraction Limited to 300nm	To provide access to UV-blue stellar populations; to resolve structure in YSO jets, protoplanetary disks, ionization fronts, etc.
Aperture	1.5-4m	This is driven by the limiting surface brightnesses and magnitudes needed traded against the necessary exposure times to achieve them – the larger the better
Stability	A small percentage of a pixel	To allow the stable photometry and astrometric measurements necessary to achieve the science goals
Photometric Stability	Combination of gain, A/D conversion and QE need to be stable to better than 10^{-5}	Again to provide the photometric stability to achieve the science goals of the project
Filter Suite	F250W, F336W, F438W, F625W, F775W, F850W; F547M, F980M, F1020M, F1050M, F1080M; F280N, F373N, F469N, F487N, F502N, F631N, F656N, F673N, F953N	Dictated by both broad-band colors needed to survey stellar populations and the narrow-band diagnostics necessary to probe the resolved gas structure and dynamics
Optical Design	Efficient design offering a wide, well-corrected field of view to be populated by a large focal plane	The science program can only be achieved by an efficient design that offers parallel observing in the red and blue, with little field distortion, and as large an objective as possible
Detectors	High yield, efficient detectors, customized in their response to the passbands needed	Tiling the large focal plane will be challenging – we need an efficient manufacture and testing process, combined with the ability to match response to the optical channels

Table 1: Science Driven General Specifications

The Magellanic Clouds Survey: a Bridge to Nearby Galaxies

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Science RFI Response to NASA Cosmic Origins Program

Abstract

To address several key Cosmic Origins program science questions, such as "**How are chemical elements distributed in galaxies and dispersed into the circumgalactic and intergalactic medium**" and "**how does baryonic matter flow from the intergalactic medium to galaxies and ultimately into planets**", we outline to the community the value of a three-phase Magellanic Clouds Survey. This survey consists of three components: I) a complete-area, high resolution, multi-band UV-near-IR broadband survey; II) a narrowband survey in 7 key nebular filters to cover a statistically significant sample of representative HII regions and a large-area, contiguous survey of the diffuse, warm ISM; and III) a comprehensive FUV spectroscopic survey of 1300 early-type stars. The science areas enabled by such a dataset are as follows: A) assessment of massive star feedback in both HII regions and the diffuse, warm ISM; B) completion of a comprehensive study of the 30 Doradus giant extragalactic HII region (GEHR); C) development and quantitative parameterization of stellar clustering properties; D) extensive FUV studies of early-type stellar atmospheres and their energy distributions; and E) similarly extensive FUV absorption-line studies of molecular cloud structure and ISM extinction properties.

Introduction & Scientific Context

This science program consists of a high spatial resolution wide field imaging survey across the Magellanic Clouds. The central goal of this program is to apply knowledge derived from local star forming environments to analogous regions where we can still resolve important physical scales to relate local star formation properties to those processes operating on global scales. The study will be extended to regions that do not have nearby analogs but are common in other external galaxies. This systematic, hierarchical approach provides for the first time a statistically supported application of local star formation knowledge to environments and conditions that do not have analogs in our own Galaxy. By extending the study to nearby galaxies we provide access to, and can study the effects of, more extreme radiation environments, lower metallicities, superbubble boundaries, and so on. We will aim to use complementary IR observations from the ground and from missions such as JWST to study the multi-wavelength properties of star forming environments, the rate of subclustering, small and large-scale feedback effects, and the propagation of star formation over a variety of spatial scales. Such a survey will require an efficient, wide-field (10s of arcmin on a side) camera on a large (~2-4 m) aperture space telescope, which will be able to map both Magellanic Clouds in their entirety at < 0.1" resolution in multiple mid-UV (~200nm)-near-IR (Y-band) broadband filters to $m_{AB} > 26$ mag and in key diagnostic narrowband filters to 10^{-16} erg cm^{-2} s^{-1} $arcsec^{-2}$.

Compelling Science Themes Based on Recent Advances

Feedback from Massive Stars

Massive OB stars have a profound influence on their environment, ranging from destructive evaporation of molecular clouds that curtails further star formation, to galactic-scale production of ionizing radiation, galactic superwinds, and heavy elements that drive evolutionary processes in galaxies and the cosmos itself. The Magellanic Clouds, owing to their proximity, known distance and minimal Galactic obscuration, are a superior test-bed in which to examine both triggering and feedback processes on both microscopic and macroscopic scales.

With such a deep, narrowband imaging survey of the Clouds, the elusive large-scale ionization structure of the diffuse, warm ionized medium (WIM) will become dramatically more apparent, allowing its spatial and ionization properties to be readily correlated with embedded star-forming regions, which presently are presumed to be the origin of the WIM. This survey will also offer important leverage on the WIM properties with respect to 3-D ISM structure and metallicity between the LMC and SMC. Comparison with the quantitative field massive star populations, as well as those in OB associations (see below) will provide unprecedented constraints on feedback parameters such as ionizing fluxes, stellar wind power, and elemental enrichment. It will be possible, with this survey dataset, to quantify and parameterize the spheres of influence of massive stars as a function of mass and interstellar conditions, for the three feedback effects.

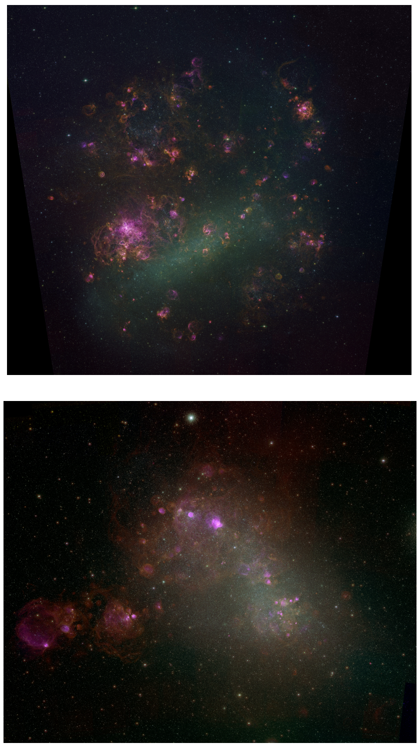

Figure 1: MCELS Mosaics of the Magellanic Clouds – this survey would offer the same coverage but at a much higher resolution and greater depth to answer a whole new set of scientific questions.

Intermediate to the large and small-scale feedback effects is the transition stage corresponding to superbubbles and supernova remnants. How energy and mass are transferred to the surrounding ISM remains to be clearly understood. Even the crude energy budgets of superbubbles are currently sketchy, with uncertainty as to whether their evolution is purely adiabatic. This survey map of the Clouds will yield high-resolution data for dozens of superbubbles and SNRs, with which the shock structures, parent stellar populations, and ionization properties can be examined in unambiguous detail. Combined with the wealth of multi-wavelength survey data (MCELS, Spitzer SAGE survey) now available for the Clouds, we will finally have an opportunity for a major breakthrough in understanding the transfer of energy from massive stars to the diffuse ISM.

30 Doradus: The Nearest Giant Extragalactic HII Region

30 Doradus is a unique, giant star formation complex in the Large Magellanic Cloud (LMC). At a distance of 51.3 kpc, 1" corresponds to a linear scale of ~0.25 pc and a 0.01" pixel would sample ~0.0025 pc or ~500 AU. The nebula is centered on a dense, massive cluster of newly formed stars, the densest component of which is called R136. The nebula itself is more than 180 pc across, which qualifies it as a smaller member of the elite class of giant extragalactic HII regions.

R136 is very compact and contains several hundred OB stars with a number of Wolf-Rayet stars. The integrated UV flux from this cluster is intense: more than 50 times that being produced in the center of the Orion Nebula. It has been shown that the majority of the stars in the cluster were formed in a single star formation event ≈2-3 Myr ago. More than 3000 stars have been resolved in this cluster of which more than 300 are OB stars capable of producing the intense UV radiation and strong stellar winds responsible for forming and shaping the HII regions we observe in galaxies. The level of star formation exhibited by the 30 Doradus region and the neighboring LMC complex are the closest examples of starburst-model type star formation and as such, from our vantage point we have a unique view of the *in situ* environment.

The 30 Doradus Nebula plays a key role in our understanding of HII regions. In nearby regions within our own Galaxy, we can study the physical processes in detail. Work on M16 has shown that emission within the nebula arises predominantly within a narrow region at the interface between the HII region and the molecular cloud. However no giant HII regions are close enough to allow the stratified ionization structure of the photoevaporative flow to be studied directly. 30 Doradus alone offers an opportunity to bootstrap the physical understanding of small nearby HII regions into the context of the giant regions seen in distant galaxies. 30 Doradus represents an entirely different class of object in terms of structure, size, dynamics, level of star formation, and diversity of morphologies.

The Clustering of Star Formation

Because of obscuration by dust, we have no clear view and understanding of star formation on large and global scales within our Galaxy. Such understanding must come from the study of other galaxies. On large scales, perhaps the most basic concept is that of a coherence length. If star formation proceeds in pockets that are independent of one another, then there should be no correlation of ages and distances between the different regions. Alternatively, if star formation propagates in a 'wave' from one side of the galaxy to the other, then there should be a linear correlation. When a star formation 'wave' dies out on scales larger than this distances (the coherence length), then the correlation between average age and separation disappears. Ground-based studies indicate that within the LMC ages and separations between star clusters are strongly correlated up to separations of ~1°. The correlation vanishes at larger separations, perhaps because the coherence length is limited by the thickness of the LMC disk or by the Jeans length.

Another fundamental parameter, hierarchical clustering, can be addressed in a similar manner with the proposed Magellanic Clouds survey. Clustering of massive stars and associations within the SMC appears to have an associated characteristic length scale of 30-60 pc. This result is very sensitive to the spatial resolution of the survey data used, underscoring the need for the high resolution of the proposed survey, which aims to quantify the, yet unknown, clustering of lower-mass stars. The characteristic clustering lengths, as a function of stellar mass, are a vital parameter for understanding the macroscopic process of star formation in galaxies. A survey assembled with a wide field of view, outstanding spatial resolution and sensitivity, will provide the perfect dataset to study coherence lengths of star formation in external galaxies. Such a survey would need to image the entire LMC and SMC in several near-UV-near-IR filters to the Main Sequence turn-off for old clusters in the LMC ($m_{AB}^{MSTO} \leq 22$ mag, at $>10\sigma$) to ultimately allow measuring the ages of each cluster individually.

Atmospheric Properties of Massive Stars

Massive, OB-type stars dominate the return of matter and energy to the interstellar medium through their dense, fast stellar winds, intense radiation fields, and eventual death and partial dispersal in supernova explosions. Consequently, the fundamental stellar parameters of these objects must be characterized accurately, in order that their evolutionary state can be inferred and their yields of energy, momentum, and chemically-enriched feedback to the ISM can be estimated reliably. These properties are an essential input to understanding the feedback cycle for both localized molecular cloud destruction and large-scale ISM and IGM feedback effects.

The availability of high-quality optical and UV spectra has shown that some fundamental aspects of the atmospheres of OB-type stars are not well understood. Uncertainties in the ionizing fluxes remain at the 0.8 dex level. There is growing evidence that the winds are not smooth and homogeneous, but are instead substantially clumped. The wind properties strongly affect the ionizing outputs through wind-blanketing in the stellar atmospheres. However, in recent years it has become apparent that the loss of angular momentum through the winds also substantially affects the stellar rotation, and therefore, the entire evolution of the stars. Thus, our survey includes an FUV spectroscopic component (down to 100nm to include specific line diagnostics) to survey OB stars in the Magellanic Clouds to fully investigate their wind properties and ionizing fluxes.

A comprehensive, FUV-UV spectroscopic survey of the hottest, most massive stars in the Magellanic Clouds will provide a data set of unprecedented diagnostic power to address these issues. The Magellanic Clouds are preferable to the Galaxy for such studies, since: (a) their distances are known, hence the luminosities of individual stars can be determined reliably; (b) a range of metallicities can be probed; and (c) the UV extinction is comparatively minor. A large aperture combined with a high-throughput FUV spectrograph will offer the spatial resolution required to observe individual OB stars in their dense natal clusters.

A new large aperture FUV facility will provide enough light-gathering power to push observations several magnitudes fainter than FUSE could reach. The type of comprehensive FUV survey of the most massive stars we have in mind will extend to spectral types of B2 V, and will include some 1300 stars. Such a large sample will overcome the small-number statistics that currently bias the available samples of Magellanic OB-stars with UV spectra, and will provide the first opportunity for complete characterization of the atmospheric properties of these populations. An important by-product will be the wealth of high-quality observations of interstellar absorption lines, that will be used to investigate the distribution and kinematics of hot (10^6 K) ionized gas, cool molecular H_2 gas, and dust properties along each sight line. The former will be especially important in studying mechanical feedback in individual star-forming regions, while also offering contrasting observations in the diffuse ISM.

The Origin and Evolution of Molecular Clouds

We propose to make a comprehensive effort to probe the origins of molecular clouds by studying both FUV absorption lines (H_2, CO, and atomic species) and extinction by dust in the LMC and SMC. A large-aperture FUV spectrograph will far surpass FUSE as a probe of molecular cloud origins at higher extinctions and with orders of magnitude more sources than FUSE could access. The key issue is how molecular clouds, the precursors of star formation, coalesce from the diffuse ISM. This process is very poorly understood in our own Galaxy because our place in the Galactic disk prevents examination of individual clouds except at very small distances. Even if Galactic trends come to be better understood, the physical processes that lead to GMC formation may depend on their environment, differing substantially in any particular galaxy that is not a spiral with modest star formation.

The different viewing geometry and morphology of the Clouds will enable detailed examination of the early evolution of molecular clouds. FUSE has demonstrated that robust star formation (via bright UV fluxes) and low metallicity (via low dust abundance) in the Clouds combine to inhibit the formation of H_2 in the diffuse ISM. FUV extinction studies of hot stars in the Magellanic Clouds show evidence for a smaller population of dust grains than in our own Galaxy. This suggests that environment affects the diffuse ISM, but it remains unclear whether and how feedback influences the GMC formation, and therefore the star formation rate and efficiency. Samples of hot stars for ISM absorption-line and extinction-curve studies can be chosen directly from the wide field imaging survey described earlier, allowing us to correlate young stellar populations with the properties of the nearby ISM gas and dust and to address the question of how GMCs arise and how star formation regulates itself on galactic scales. This ambitious goal requires both accurate photometry for the stellar populations (to derive reddening for the candidate stars) and a high-throughput FUV spectrograph. These data will extend the excellent work done in the MCs by FUSE to new "extragalactic galactic" environments. One of the legacies of the FUSE mission is its detailed study of the interstellar medium of the Small and Large Magellanic Clouds, using roughly 200 observations of OB stars. With as much as 25 times the effective collecting area, FUSE's work can be extended to higher extinction at twice the resolution.

Broad Design Specifications Driven by this Science

To achieve the science goals of this program a variety of capabilities need to be implemented. The majority of the tracers and the various phases of the ISM and stellar populations being targeted require the angular resolution and wavelength agility of a medium to large aperture (2-4m) UV/optical space telescope combined with a wide-field imaging camera that can provide diffraction-limited images into the UV-blue to capture the UV-bright stellar populations that HST has only been able to recently reach with the installation of WFC3/UVIS. Such a telescope needs to be located in an orbit that is both dynamically and thermally stable (such as L2) to produce the photometric stability required by many aspects of the science goals. A broad complement of both wide- and narrow-band filters will be necessary to isolate and measure not only the unique tracers of specific atomic species but also the trends in stellar color across entire swaths of our local Galactic neighborhood. This project requires the combination of the wide field, high resolution imager with a high-throughput FUV spectrograph capable of detecting down to 1000Å to provide access to key diagnostic lines. Such a capability will require the development of reliable coatings that are highly reflective in the FUV and that can be applied to larger optics than has been achieved so far. Next generation UV detectors provide the efficient detection of weak signals will also be necessary to make this capability efficient and reliable.

While the science program in this paper have defined a loose set of specifications (see Table 1), it should be recognized that the opportunity for truly unique discovery is made possible by the **combination** of both a wide angular field of view (tens of arcminutes on a side) **with** the diffraction limit of a medium to large aperture in the UV/optical (resolution elements below 10-20 mas). HST and JWST have provided and will provide exquisite resolution but can efficiently survey only over very small fields of view.

Four Central Questions to be Addressed

1. What is the nature of the interrelation between the formation, evolution and destruction of massive stars and the energization of the WIM? How does the formation of massive stars in a particular locale affect and dictate the subsequent star formation across that region?
2. What is the fundamental difference between starburst star formation and the more common disk modes we see in disk star forming regions in our own Galaxy? What causes the several orders of magnitude increase in star formation efficiency as well as the almost instantaneous formation of thousands of stars at once?
3. What is the correct density and velocity structure associated with the stellar winds from massive stars? How does inhomogeneity and clumping in these winds affect the transfer of energy and material to the ISM and the process of recycling of material from the stellar to the gas phase for the next generation of stars?
4. What are the global processes that govern the assembly and evolution of giant molecular clouds? Since these nurseries host the most dominant modes of star formation in galaxies, we need to understand the nature of their formation and development if we are to understand the underlying process of stellar assembly.

Parameter	**Specification**	**Justification**
Field of View	At least 200 sq. arcmin	To allow a statistically complete survey of as many targets and environments as possible in a reasonable period of time
Resolution	Diffraction Limited to 300nm	To provide access to UV-blue stellar populations; to resolve structure in ionization fronts, etc.
Aperture	1.5-4m	This is driven by the limiting magnitudes needed traded against the necessary exposure times to achieve them – the larger the better
Stability	A small percentage of a pixel	To allow the stable photometry and astrometric measurements necessary to achieve the science goals
Photometric Stability	Combination of gain, A/D conversion and QE need to be stable to better than 10^{-5}	Again to provide the photometric stability to achieve the science goals of the project
Filter Suite	F250W, F336W, F438W, F625W, F775W, F850W; F547M, F980M, F1020M, F1050M, F1080M; F280N, F373N, F469N, F487N, F502N, F631N, F656N, F673N, F953N	Dictated by both broad-band colors needed to survey stellar populations and the narrow-band diagnostics necessary to probe the resolved gas structure and dynamics
Optical Design	Efficient design offering a wide, well-corrected field of view to be populated by a large focal plane	The science program can only be achieved by an efficient design that offers parallel observing in the red and blue, with little field distortion, and as large an objective as possible
Detectors	High yield, efficient detectors, customized in their response to the passbands needed	Tiling the large focal plane will be challenging – we need an efficient manufacture and testing process, combined with the ability to match response to the optical channels
Coatings	Development of stable, high-reflectivity FUV mirror coatings	To provide high throughput access to the FUV (below 115nm) while minimizing risk to the optical reflectivity of an optical system
FUV Detectors	Development of next generation MCP technology	To provide a low-cost, high QE, robust solution to allow efficient observations of FUV emission, below 115nm to as low as 100nm
FUV Spectroscopic Resolution	R > 30,000	To enable sufficient resolution to see structure and dynamics of emission from science targets

Table 1: Science Driven General Specifications

RESPONSE TO RFI "SCIENCE OBJECTIVES AND REQUIREMENTS FOR THE NEXT NASA UV/VISIBLE ASTROPHYSICS MISSION CONCEPTS"

MASSIVE STARS: KEY TO SOLVING THE COSMIC PUZZLE

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Abstract. We describe observations in the nearby universe (<100 Mpc) with a ≥10-m space-based telescope having imaging and spectral capabilities in the range 912-9000 Å that would enable advances in the fields of massive stars, young populations, and star-forming galaxies, that are essential for achieving the Cosmic Origins Program objectives i) how are the chemical elements distributed in galaxies and dispersed in the circumgalactic and intergalactic medium; and ii) when did the first stars in the universe form, and how did they influence their environments. We stress the importance of observing hundreds of massive stars and their descendants individually, which will make it possible to separate the many competing factors that influence the observed properties of these systems (mass, composition, convection, mass-loss, rotation rate, binarity, magnetic fields, and cluster mass). AW would be willing to participate and discuss the content of this paper at a workshop if invited.

1. ESSENTIAL ADVANCES IN MASSIVE-STAR ASTROPHYSICS

Motivation. Massive stars (≥8 $M_\odot$) play seminal roles in the chemical enrichment and evolution of galaxies. They produce the bulk of the α-elements, e.g., oxygen (Weaver & Woosley 1995, Woosley & Weaver 1995), some of the Fe and Fe-peak elements (François et al. 2004), and at low metallicity, significant amounts of C and N (Pettini et al. 2008, Chiappini et al. 2006). They also craft the interstellar medium through their winds and explosive deaths (Mac Low & McCray 1988), enrich the circumgalactic medium (CGM, Tumlinson et al. 2011), dominate the spectral energy distribution of star-forming galaxies (Leitherer et al. 1999), are essential for understanding the energetics of galactic centers, and are related to very energetic and disruptive processes like supernovae (II, Ib/Ic, and Ia) and possibly long gamma-ray bursts (Dessart et al. 2012). In addition they produce (Gall et al. 2011) and destroy dust. Finally, massive stars may be responsible for causing reionization in the early Universe (Robertson et al., 2010; Heckman et al. 2011). Interesting physics of massive stars include atomic processes, radiative transfer in complex media, stellar wind/ISM interactions, interacting binary evolution, radiation-(magneto)hydrodynamics, shocks, and production of X-rays.

The winds of blue massive stars (BMSs). The term blue massive stars encloses OB stars with masses ≥20 $M_\odot$, Wolf-Rayet (WR) stars, and Luminous Blue Variables (LBVs). These stars experience radiation-driven outflows of matter, or winds, propelled by the absorption of photons in the numerous UV transitions of metallic ions (Kudritzki & Puls, 2000). The stellar wind is the main interface of pre-supernova massive stars with the interstellar medium through the injection of mechanical and radiative energy, and chemically enriched material. The wind is also a principal agent of the evolution of the massive star itself. Because of the wind mass removal, the rate and efficiency of the central nuclear reactions change, altering the duration of the evolutionary stages and ultimately deciding the fate of the star (the SN explosion, the stellar yields, and the remnant; Georgy et al., 2009; Matteucci, 2008; Woosley et al., 2002). The stellar wind leaves a significant imprint on the observed spectra of BMSs at different wavelength ranges (see the review by Kudritzki & Puls 2000 and more recently Martins 2011). Its main parameters, mass loss rate ($\dot{M}$) and terminal velocity (v_∞) can consequently be derived from quantitative spectral analysis using model atmospheres that include radiation driven winds (e.g., Puls et al., 2005; Pauldrach et al., 2001; Hillier & Miller, 1998; Bianchi et al., 2009). However, the wind signatures also alter line diagnostics for other stellar parameters. For instance, the wind enhances the line blanketing effect and fills the He II lines, which are critical to determine T_{eff} in O stars (Repolust et al., 2004). The photospheric and wind parameters must be determined jointly.

Uncertain mass-loss rates. In order to interpret distant unresolved starbursts and their effects on their environments, but also feedback into the ISM and CGM, it is essential to understand the structure and evolution of massive stars observable at high spectral and spatial resolutions. That is far from the case at present, even for their relatively quiescent early evolutionary phases, and it is partly due to remaining unexplained points regarding the winds of BMSs. For instance, the issues of inhomogeneities and asymmetries in their powerful winds, which substantially affect their mass-loss rate estimates, and therefore, our knowledge of their evolution, are matters of debate. In addition, the potential dependences of these effects on metallicity have hardly been addressed at all.

Unknowns in the final stages of massive stars. The situation regarding our knowledge of the advanced evolution and endpoints of massive stars is even worse: there is a zoo of peculiar objects of uncertain or unknown interpretation, and the progenitors of the diverse categories of core-collapse supernovae are unidentified except for those of the lowest masses. The foregoing refers primarily to simple, single stars; complicating factors such as rapid rotation, magnetic fields, and binary interactions are only beginning to be addressed. Vast observational and theoretical efforts will be required to improve this situation.

Ultraviolet is key. The far-ultraviolet (900-1200 Å, FUV) and ultraviolet (1200-2000 Å, UV) are the only ranges where terminal velocities of O and early-B stars can be derived from. The value of v_∞ is calculated from the bluest extent of the Doppler-shifted absorption of P-Cygni profiles of resonance lines in these spectral ranges: O VI 1031.9,1037.6, S IV 1062.7,1073.0,1073.5, the C IV 1169+C III 1176 blend, N V 1238.8,1242.8, Si IV 1393.8,1402.8 and C IV 1548.2,1550.8 (Kudritzki & Puls, 2000; Martins, 2011). When no such spectra are available, the terminal velocity of OB stars is estimated from calibrations with spectral type (Kudritzki & Puls, 2000) or from the escape velocity ($v_\infty/v_{esc} \approx 2.6$ for $T_{eff} > 21{,}000$K; $v_\infty/v_{esc} \approx 1.3$ for $T_{eff} < 21{,}000$K, Lamers et al. 1995), and then scaled with metallicity ($v_\infty \propto Z^{0.13}$, Leitherer et al. 1992). However we need to produce calibrations for critical transitional phases (early WR, Ofpe/WN9 stars etc.), where $\dot{M}$ varies highly. The UV lines are also essential (combined with e.g., Hα) to constrain clumping factors, which are needed for a precise measurement of $\dot{M}$ (Bouret et al. 2005; Fullerton et al. 2006; Herald & Bianchi 2011; Bianchi et al. 2009).

Metallicity and wind parameters. Theory predicts a strong correlation between the momentum carried by the wind and the luminosity of the star and metallicity: the wind-momentum luminosity relation (Kudritzki et al., 1995). This relation has been proved empirically, and its metallicity dependence empirically characterized from the Milky Way (MW) down to the metallicity of the Small Magellanic Cloud (SMC) (Vink et al., 2001; Mokiem et al. 2007). Very low metallicity BMSs are expected to experience weaker winds than SMC stars and much weaker winds than MW stars (see Fig. 1). However, some recent results are in marked contrast. Tramper et al. (2011) reported 6 stars with stronger wind momentum than expected at the poor metallicity of their host galaxies (~ 1/7 $Z_\odot$, IC1613, WLM and NGC3109) from X-Shooter spectroscopic analyses, although error bars are too large for results to be determinant. Herrero et al. (2012) report the analysis of an Of star in IC1613 that may also have a strong wind or, alternatively, a lower than expected wind acceleration. These examples, if confirmed by a large sample of objects, pose a challenge to the theory, as there are few metals to drive the wind. Yet, this might explain why long-GRBs (typically associated with type Ic SN, Woosley & Heger, 2006) are mostly found in metal-poor environments (Modjaz et al., 2008; Levesque et al., 2010) but require a strong wind to remove the H and He envelope in the pre-SN stages. However, the studies of the winds of BMSs beyond the Magellanic Clouds are based only on optical data, hence lack direct measurements of the terminal velocity and introduce large error bars in the wind-momentum luminosity relation.

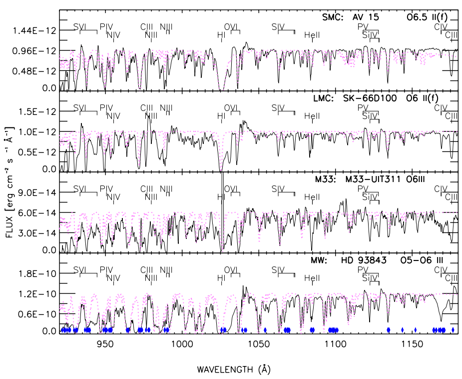

Fig. 1 FUSE spectra of BMSs with approximately the same spectral type in the SMC, LMC, outer-M33 and MW. Diamonds mark interstellar and airglow transitions, while the dotted line is a model for hydrogen absorption towards the targets. The stellar spectra (black solid line) display lines of OVI, PV and CIII which develop a weaker wind profile (even photospheric) as the metallicity decreases, i.e., as we move upwards in the plot.

Past UV observations. The *International Ultraviolet Explorer* (*IUE*) provided a sample of ~200 Galactic OB spectra at high resolution (R~10^4) in the 1200-1900 Å range. The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) observed a few tenths of stars from 900-1200 Å in both the Galaxy (Pellerin et al. 2002) and the Magellanic Clouds (MCs, Walborn et al. 2002), the latter providing vital information at lower metallicities (about 1/2 solar in the Large Magellanic Cloud and 1/5 in the Small Magellanic Cloud). However, the *Hubble Space Telescope* has so far failed to realize its potential to provide the corresponding 1200-1900 Å data for an adequate sample in the Magellanic Clouds, only a few tens of OB UV spectra having been observed at high resolution in the Small Cloud, and even fewer in the LMC. The existing *HST* sample does not cover the relevant parameter space either for OB astrophysics or as a reference to model distant starbursts (lower metallicities than in the MCs are required). The main reasons for this shortcoming appear to be the heavy oversubscription of *HST* by multiple instrument configurations and the inefficiency of observing individual stars.

Role of a ≥10-m telescope. i) UV spectroscopy for a statistically significant sample of OB stars in the Local Group galaxies, including the Magellanic Clouds. A multiple-object UV spectrograph would enable to obtain an adequate sample, just as large ground-based telescopes have in the optical. For instance, the Sanduleak objective-prism survey of the LMC (Cerro Tololo Inter-American Observatory Contribution No. 89, 1970) identified the 1200 brightest, isolated OB supergiants, including the progenitor of SN~1987A, which was unfortunately not seriously observed even in the optical prior to the arrival of the event. One can estimate that there are 1000 SN events on the way from the MCs; hopefully we might have done better before the next one arrives. If the spectrograph could do 100 objects at a time, this survey would be covered in 12 exposures; of course, multiple exposures are desirable to improve signal-to-noise and address variability. However, this sample is the tip of an iceberg. For instance, the (ESO) VLT-FLAMES Tarantula Survey in 30~Doradus/LMC (Evans et al. 2011), the largest starburst region in the Local Group, has obtained high-resolution spectroscopy of 800 OB stars in that field alone, which are currently being analyzed with all state-of-the-art observational and theoretical techniques and will provide unprecedented information about massive stellar and cluster evolution on this scale. However, without the UV to constrain wind and photospheric parameters (including the bolometric luminosity and masses), the huge potential of this surveys, and of similar large investements of ground-based telescopes, cannot be fully realized. Most of these stars are fainter and more heavily extincted than those in the Sanduleak survey, but feasible with a 10-meter space telescope. We shall never understand distant starbursts until we understand the intricate, multiple stellar populations and generations in 30~Doradus, as well as other nearby objects such as Henize N11 in the LMC, a once and future 30~Doradus about 2~Myr older, which is a significant difference on the evolutionary timescales of the most massive stars. GALEX has just finished observing the entire LMC and SMC in the NUV, allowing generation of a panchromatic catalog of UV-bright stars (Thilker et al. in prep). This survey will enable careful vetting of potential targets for UV spectroscopy, thereby maximizing the return from a systematic 10-m observing campaign.

ii) Stellar astrophysics in a range of metallicity environments and conditions. The telescope would produce reliable measurements of the wind parameters, and enable firm conclusions regarding the effect of metallicity on the wind momentum of BMSs. To widen the studied metallicity range we need to reach farther into the Local Group: M31, M33 and the dwarf irregulars (Garcia et al., 2011b, Bianchi et al. 2011, 2012a, b). However, single-object UV spectroscopy beyond the MCs is very expensive in observing time, even with HST's lowest resolution spectrograph (G140L, R ~ 2600 at 1550 Å). A recent HST treasury program has imaged six nearby star-forming galaxies with a key set of filters including 2 filters shortward of the U band. Results showed a huge variety of properties of the massive star content. At a distance of 18 Mpc, I Zw 18, the most metal-poor star-forming galaxy found in the local universe is beyond the reach of current instrumentation to perform studies of stars equivalent to those done in our Galaxy and the Magellanic Clouds. For reasons still not understood, this galaxy has maintained its near-pristine chemical composition of ~1/30 the solar value ($Z_\odot \approx 0.13$) since the epoch of galaxy formation. Its stars are the closest local counterparts in terms of composition to the first stellar generation formed in the early universe. A 20 m telescope at 1500 Å will resolve 0.1 pc in I Zw 18; comparable to resolution in 30 Doradus in V from ground (see Fig. 2).

Fig. 2. I Zw 18. A few numbers for this galaxy are:

- D = 18 Mpc (m – M = 31.3); 88.5 pc/arcsec; v_{helio} = 750 km/sec
- 370× more distant than 30 Doradus
- Individual O star has ~ 10^{-18} erg/s/cm^2/Å at 1500 Å; this is still well above the sky background
- B0 main-sequence star has V ≈ 27; solar-type star has V ≈ 36
- Foreground reddening E(B – V) = 0.03; negligible internal reddening (ideal for UV)

2. RESOLVED YOUNG POPULATIONS IN EXTREME ENVIRONMENTS

Motivation. Spatially resolved imaging and spectroscopy of young populations in uncharted extreme environments are essential for understanding hypergiant stars, and the properties of systems more massive than 30 Dor, the mini-starburst in the LMC, i.e., their star formation rates, their star formation histories, their structure, and the effects of very low metallicity on their UV spectra and their initial mass functions (IMFs).

Hypergiant stars. Candidates for isolated BAF-type hypergiant stars are found in the Antennae (Whitmore et al., 2010). Can they be confirmed, and what are their properties? **Higher stellar population mass regimes.** The detailed structure of starbursts several times larger and more massive than 30~Dor can also be discerned in *HST* images of the Antennae major merger at about 20 Mpc. What are their properties? Are they related to globular clusters? **Star formation rates.** In general, the infrared through Hα to UV represents a sequence of increasing age for young populations, so all three regimes are essential for accurate determination of star-formation rates. For example, NGC 604 in M33 (Fariña et al. 2012) provides a more massive version of N11 containing at least four stellar generations. **Star formation histories.** Wide-field observations of star-forming regions are important for understanding star formation histories. On small spatial scales, the OB clusters in the circumnulear starburst region of M83 appear to have formed in a spatially uncorrelated manner, while on larger spatial scales, they show an age gradient along the starburst's arc, which is a few hundred parsecs long (Wofford et al. 2011). **The structure of superstar clusters.** NGC~5471 in M101 (García-Benito et al. 2011) is a spectacular cluster of superclusters. Improved observation and analysis of such systems will surely be relevant to more massive starbursts than 30~Dor. **Star cluster properties at very low metallcity.** Chemical composition is the key parameter that determines properties such as the stellar initial mass function (arguably), the stellar mass-luminosity relation, stellar lifetimes, the escape of stellar radiation, or release of matter from massive stars to the interstellar and intergalactic medium. Investigating the influence of chemistry on the physics of stars and resolved stellar population is a premier goal of contemporary astrophysics. As an example, I Zw 18 has a record-setting chemical composition that causes truly transformative changes in stellar properties, as opposed to incremental differences when moving, e.g., from our Galaxy to the Small Magellanic Clouds (see fig. 3). I Zw 18 will turn out to be the Holy Grail of extragalactic stellar astrophysics of massive stars.

Role of a ≥10-m telescope. Such a telescope could provide complete CMDs of star-forming regions down 1 solar mass, IMFs, high-resolution UV/optical spectra of individual OB stars, low-resolution SEDs of individual stars, and emission- and absorption spectra of the ISM in galaxies covering a range of conditions, which are all useful for input in stellar population synthesis codes and the interpretation of unresolved young populations.

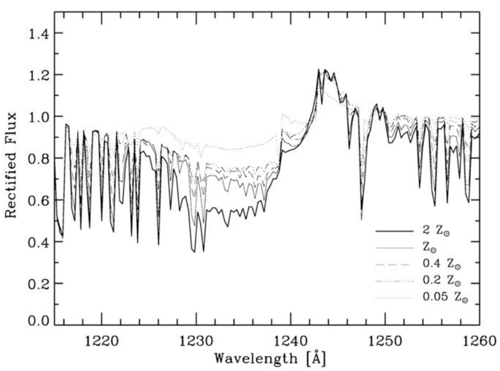

Fig. 3 The N V P-Cygni profile of a synthetic stellar population as a function of metallicity. The metallicities of the LMC, SMC, and I Zw 18 are the bottom three values.

3. EXTRAGALACTIC EXTINCTION

Motivation. The UV-spectra of individual massive stars is very sensitive to extinction by dust and localized dust characteristics must be derived concurrently with the stellar parameters. Regarding young populations, twenty percent of their luminosity is emitted in the wavelength range 912-1200 Å, where the reddening curve peaks and where our knowledge of the reddening due to dust is still fragmentary (Leitherer et al. 2002, Buat et al. 2002, Wofford et al. in prep.). The spectral energy distribution (SED) of star-forming galaxies in the FUV is determined by the stellar IMF, the recent star formation history, and the dust extinction. Therefore, FUV observations of star-forming galaxies are fundamental for understanding the above properties and to interpret the spectra of high-z galaxies.

Deriving selective extinction curves. The standard technique to derive the extinction curve in stars is to observe stellar pairs of identical spectral types, one member of the pair being heavily reddened and the other unreddened. Comparison of the two SEDs allows the determination of the selective extinction curve $A\lambda/E(B-V)$. Applied to galaxies, the approach is similar, except that dust-free synthetic stellar population models are used instead of the unreddened spectrum. Alternatively, one can use low extinction observations as the unreddened galaxy spectrum.

Past Work. The mean UV extinction law for the SMC is usually taken as a template for low-metallicity galaxies. However, its current derivation is based on only five stars, which renders its universality questionable (Maíz Apellániz & Rubio 2012). Our scarce knowledge of extragalactic extinction has limited us to adopt average extragalactic extinction curves for heterogeneous sets of galaxies, dust compositions, and dust geometries. As illustrated in Fig. 4, it is important to push the limit with a ≥10-m telescope and produce reliable selective extinction curves.

Role of a ≥10-m telescope. A wide-field imager with a slitless spectrograph would enable an in-depth study of the dust extinction in the MCs and beyond by producing i) low-resolution spectra and ii) panchromatic photometry of resolved stars that would characterize their SEDs. The range 912-3000 Å is key as it includes the FUV and the 2175 Å extinction bump, which yields information about the dust composition. *HST* has been able to detect individual bright stars in the Local Group galaxies and a larger telescope will be able to probe fainter.

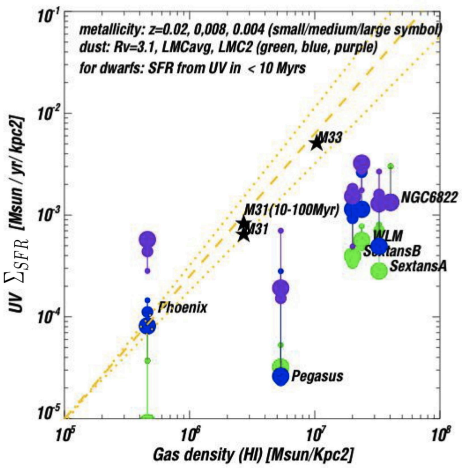

Fig. 4 The importance of proper reddening corrections to derive star-formations rates from UV fluxes. Average SFR per unit area versus gas density for 6 Local Group dwarfs, derived from GALEX measurements of individual star-forming sites in these galaxies, assuming 3 different extinction curves, and E(B-V) derived for each region from the massive stars it contains (characterized with HST data). The figure (Bianchi et al. 2011) illustrates how the results depend on metallicity and assumed dust extinction curve. Yellow lines show the "Kennicut-Schmidt law" which was defined for disk galaxies (Rowchowdhury et al. 2009).

4. Lyα FROM GALAXIES AT z~0

Motivation. Lyα is the only emission line that we can detect from the highest redshift galaxies (z>6). Thus, it is our only probe of the internal structure of these galaxies, and it is one of our few diagnostic tools for studying the IGM at these high redshifts. The advent of WFC3 on HST has resulted in the detection of galaxies out to z ~ 10. If at these high-redshifts we can determine the detailed Lyα line profile that emerges from the galaxy, and the fraction of the line flux that escapes the galaxy, then we can use Lyα as a probe of the ionization history of the intergalactic gas, and study the nature and evolution of high-redshift galaxies. In order to determine the intrinsic Lyα properties of distant galaxies, it is useful to study lower-redshift samples where we can separate the effect of the IGM from the galaxy. In addition, detailed studies of the Lyα escape problem are only possible at low z, where the galaxies are resolved.

Results from past-studies. Low-redshift HST/ACS/SBC Lyα-line images have uncovered the presence of a diffuse Lyα component around concentrated knots of star-formation (Ostlin et al. 2009) that contributes to a significant fraction of the total Lyα emission from the galaxies. These images and recent HST/COS spectroscopy (Wofford et al., subm.) show the simultaneous presence of Lyα in emission and absorption in the same object within spatial scales of a few parsec, which highlights the importance of the ISM geometry in determining the escape fraction of Lyα photons from galaxies.

Role of a ≥10-m telescope. A wide filed telescope with imaging and spectroscopic capabilities, and having a spectral resolution of FWHM ≤ 50 km/s in the far-ultraviolet would enable a) to observe a statistically significant sample of nearby isolated disk galaxies with different inclinations so that the Lyα escape fraction can be studied as a function of inclination (unprecedented and essential); b) create maps of the Lyα emission and dust distribution in galaxies down to the spatial scales of ISM and circumgalactic clumps, i.e., <1 pc, using appropriate extinction curves (see previous section, unprecedented), and c) understand the relative importance of dust, H I column density, gas outflows, gas geometry, and stellar-population properties on the escape fraction and line profile of Lyα photons, at low-redshift.

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CONDITIONS FOR LIFE IN THE LOCAL UNIVERSE

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Science Description

Some of the greatest outstanding scientific questions of our day are connected to the existence of life in the Universe, the necessary conditions for this and its sustainability. An underpinning factor is the creation of the elements and the flow of this material within our own and other galaxies leading to the birth of stars and planetary systems, leading perhaps to the environments needed for life to be established. The pieces of the scientific jigsaw puzzle that will ultimately lead to a complete understanding are broad in temporal and spatial scope, encompassing the earliest phases of the Universe, observed at high red shift, through to the galactic environment of the Solar System within as little as a few parsecs. This RFI response addresses the "local" aspect of the cosmic feedback and flow of baryons to support life, assuming that other elements will be considered in complementary submissions.

The Sun and several nearby stars are embedded in a complex of warm (~7000 K) and partially ionized interstellar clouds. In turn, this complex resides in an unusually low neutral gas density part of our Galaxy, a ~100 pc diameter rarefied cavity often termed the 'Local Bubble'. This region is filled with a diverse population of stars and its structure has been influenced by their lifecycles, which have, conversely, been affected by the environment in which they exist. We need to understand this cosmic feedback system within the local bubble and how it ultimately influences the habitability of our region of the Galaxy. This requires an understanding of the physics that controls the evolution and characteristics of hot atmospheres and coronae and the resulting interplanetary environment, linking the effects of stellar activity to habitability in stellar planetary systems. It addresses three key aspects of the COR program.

- What are the mechanisms by which stars and their planetary systems form?
- How are the chemical elements distributed in galaxies and disperse in the circumgalactic and intergalactic medium?
- How does baryonic matter flow from the intergalactic medium to galaxies and ultimately into planets?

The formation and evolution of stars, their interaction with interstellar material and the ultimate effect of all the various physical processes on their planetary systems is still poorly understood. Crucial elements of the picture concern the levels of activity in main sequence stars and the resulting stellar winds, which can directly affect planetary environments on a range of timescales. In addition, stellar winds control the flow of material and flux of cosmic rays from the galactic environment, which also have a potential influence on climate. Ultimately, stars recycle material back into the ISM enriching galactic metal content, through the production of white dwarfs and supernovae. All the important processes involved in these stellar lifecycles are traced by the presence of hot (10^5-10^7 K) gas. The important atomic transitions associated with this high temperature material occur in the UV, making the availability of UV imaging and spectroscopy essential for this work.

Specific science questions to address are:

Examine the structure and dynamics of stellar coronae: to determine the origins and evolution of coronal activity over stellar lifetimes and the influence of this activity on exoplanet atmospheres, astrospheres and the ISM.

Study the evolution of white dwarfs: to examine the physical mechanisms controlling the atmospheric abundances and understand how important elements such as CNO are returned to enrich the interstellar medium; determine the incidence of circumstellar material associated with the disruption of remnant planetary systems.

Probe the structure & ionization of the Interstellar Gas in the Galaxy and in the local group: measuring density, temperature, ionization state, and depletion level of gas clouds along 100s of lines-of-sight. Study local bubble-like structures in external galaxies.

General instrument requirements

This programme requires a range of instrumental capabilities including high-resolution imaging and spectroscopy. The principle drivers for the instrument requirements are:

- Highest possible spectral resolution (R>100,000) to distinguish multiple interstellar cloud components in velocity space.
- High instrument effective area to keep exposure times low and allow large samples (100s to 1000s) of objects to be observed (targets mostly too spatially dispersed for multi-object spectroscopy).
- High resolution imaging, capable of studying 10s of parsec size structures in local group galaxies.
- Wavelength range 100-300nm.

M.A. Barstow – 10th August 2012

I am willing to attend and participate in a workshop if invited

Response to Solicitation NNH12ZDA008L: Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts

Title: The History of Star Formation in Galaxies

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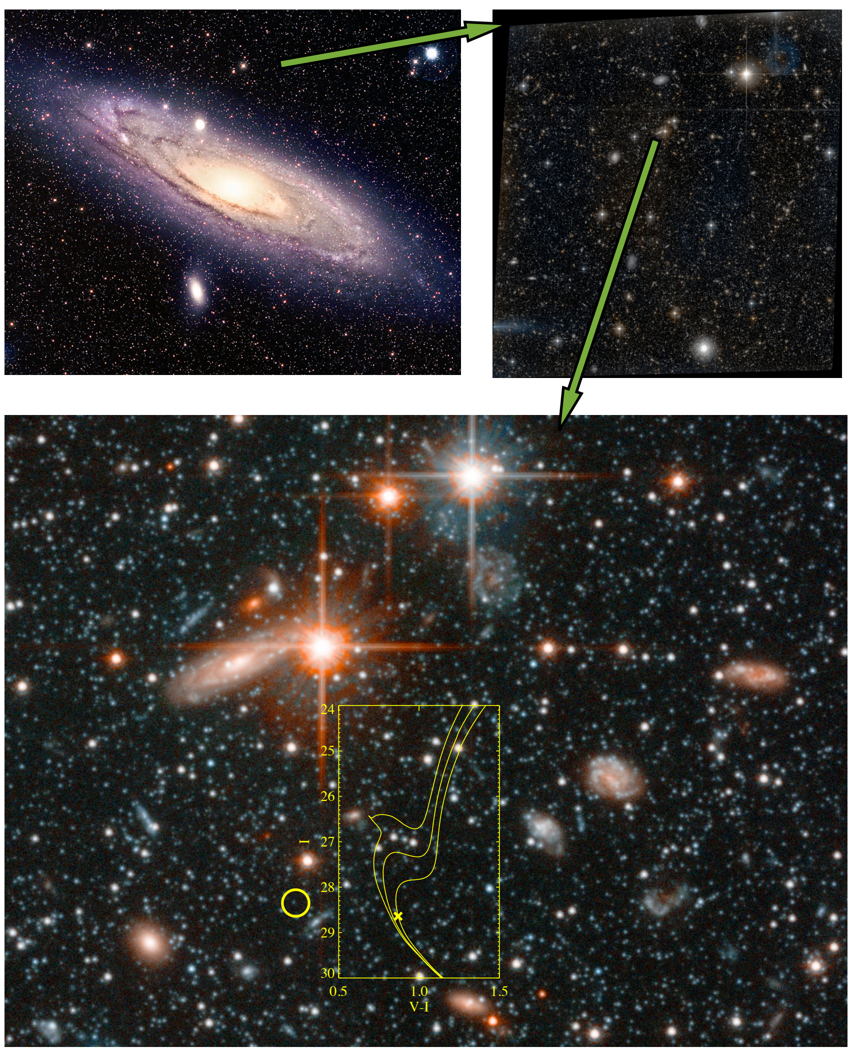
Willingness to participate and present at NASA workshop: Yes



Abstract

If we are to develop a comprehensive and predictive theory of galaxy formation and evolution, it is essential that we obtain an accurate assessment of how and when galaxies assemble their stellar populations, and how this assembly varies with environment. There is strong observational support for the hierarchical assembly of galaxies, but our insight into this assembly comes from sifting through the resolved field populations of the surviving galaxies we see today, in order to reconstruct their star formation histories, chemical evolution, and kinematics. To obtain the detailed distribution of stellar ages and metallicities over the entire life of a galaxy, one needs multi-band photometry reaching solar-luminosity main sequence stars. The *Hubble Space Telescope* can obtain such data in the low-density regions of Local Group galaxies. To perform these essential studies for a fair sample of the Local Universe, we will require observational capabilities that allow us to extend the study of resolved stellar populations to much larger galaxy samples that span the full range of galaxy morphologies, while also enabling the study of the more crowded regions of relatively nearby galaxies. With such capabilities in hand, we will reveal the detailed history of star formation and chemical evolution in the universe.

Introduction

The study of galaxy evolution is pursued on two distinct fronts: the high-redshift universe and the local galactic neighborhood. In the high-z universe, we are directly observing the evolution of galaxies with time in an enormous sample of galaxies, but the properties of interest (morphology, kinematics, age, metallicity) are not directly accessible; instead, crude and degenerate diagnostics can be used in a composite sense on the scale of a resolution element. In the local volume, we can use methods that accurately measure these properties in resolved stellar populations, but we can only do so in a small sample of galaxies as they presently exist. High-redshift and galactic neighborhood studies are clearly complementary, but together they do not yet adequately explore the required parameter space. Progress in high-z work will require pushing back to the time of first light and the birth of galaxies, while progress in the local volume requires we accurately measure star formation histories beyond the Local Group.

The most robust method for measuring the star formation history of a stellar population comes from analysis of a color-magnitude diagram (CMD) that includes both the bright giant stars and the faint dwarf stars. Today, the *Hubble Space Telscope (HST)* can obtain the detailed star formation history in populations within a Mpc, but unfortunately our immediate neighborhood is too rural for such work (see van den Bergh 2000). The Local Group is a cosmological backwater, with only two giant spiral galaxies (the Milky Way and Andromeda) and a few dozen dwarf galaxies (mostly in orbit around the two giants). Some of the major morphological classes are not represented at all (e.g., giant elliptical and lenticular galaxies), and even the classes that are represented are not present in statistically meaningful numbers. For example, the intermediate-mass spiral M33 is the most common type of spiral in the universe (Marinoni et al. 1999), but M33 is the only representative of such a system in the Local Group. Beyond the Milky Way system, we have obtained a handful of *HST* pencil beams through some Local Group galaxies, but we simply have not characterized the assembly history in a representative sample of galaxies nor done so over a representative range of substructures of the known galaxy classes. The result is that our understanding of the star formation history in galaxies is highly skewed toward the few accessible examples (in the case of spirals) or based upon indirect and degenerate diagnostics (in the case of ellipticals, which are currently too distant for direct methods). Even so, the small steps we have taken so far have changed the way we view the assembly of galaxies, and obtaining a fair sample of stellar populations in galaxies is assured to yield substantial breakthroughs.

We shall use the recent exploration of Andromeda (M31) as an example. Out to a distance of ~25 kpc in the M31 halo, the metallicity exceeds that in our own halo by an order of magnitude (Mould & Kristian 1986; Durrell et al. 1994, 2001). These studies obtained the metallicity distribution from the colors of red giant branch (RGB) and asymptotic giant branch (AGB) stars. In principle, the luminosity distributions of the RGB and AGB stars also provide insight into the age of a population, in broad age bins of young (< 3 Gyr), intermediate age (3 - 8 Gyr), and old (8 - 13 Gyr) stars. In practice, obtaining these luminosity distributions is difficult to accomplish in sparse field populations, due to the combination of photometric scatter, broad metallicity range, uncertainties in apparent distance modulus, poor statistics for the brightest giants, and contamination from foreground stars and background galaxies. As a consequence, the M31 halo was assumed to be ancient (> 10 Gyr old). That picture changed when *HST* was able to image faint main sequence stars in M31 (albeit outside of the crowded interior). The M31 halo was found to host significant numbers of intermediate-age stars, presumably from a significant merger event (Brown et al. 2003; Fig. 1). A followup program probed the giant tidal stream and outer disk of M31 with main sequence photometry. The metallicity and age distributions in the stream were found to be very similar to those in the halo, suggesting that the halo was polluted with the debris from this disrupted satellite (Brown et al. 2006). This hypothesis was further borne out by N-body simulations (Fardal et al. 2007) and kinematic surveys (Gilbert et al. 2007). The population in the outer disk of M31 appears to be similar to that in the local Galactic thick disk, and does not include as many young stars as some disk formation models predict (Brown et al. 2006). Around the same time, an extended metal-poor halo was found in M31 (Guhathakurta et al. 2005; Irwin et al. 2005; Kalirai et al. 2006), spanning 20 degrees on the sky. There was speculation that this outer halo was the "true" halo, perhaps being both metal-poor and ancient, but deep photometric programs found intermediate-age stars in the extended halo as well (Brown et al. 2008). While semi-analytical models of galaxy formation have been used to simulate merger histories for the giant galaxies (e.g., Bullock & Johnson 2005), they have not made firm predictions on the distributions of age and metallicity in the disrupted satellites. These star formation history investigations and others like them are starting to provide the data required to constrain the populations in these hierarchical assembly histories (e.g., Font et al. 2008). Ironically, we know more about the age distribution in the M31 halo than we do in the Milky Way halo, due to reddening and distance uncertainties in the latter. There is some indication the Galaxy has had an unusually quiescent merger history, and that M31 is more representative of giant spiral galaxies (e.g., Hammer et al. 2007), but there is no way to know the variety of star formation histories in galaxies without a significant sample to explore.

The reconstruction of star formation histories in a wide range of galaxy types will reveal not only

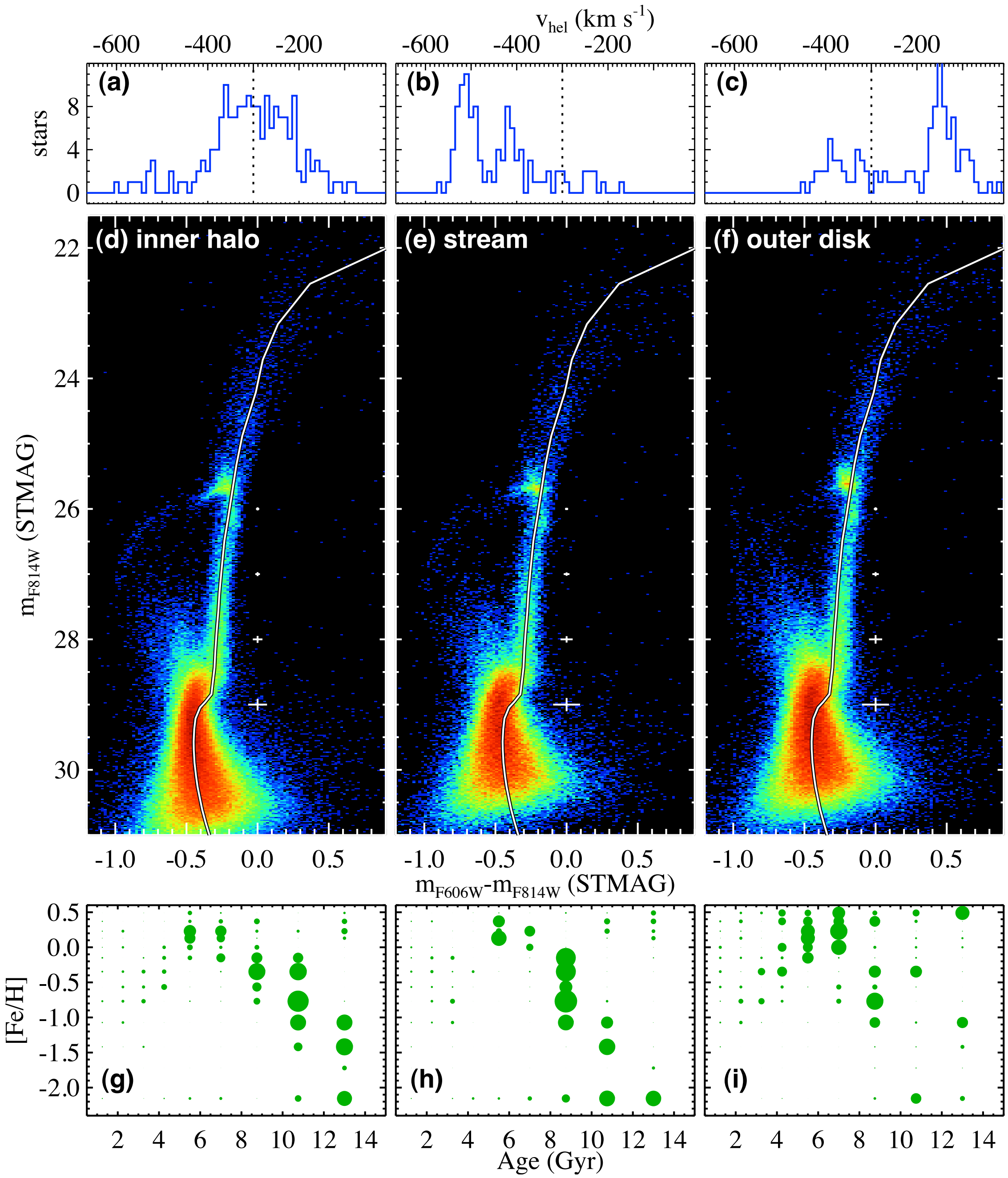


Fig. 1 - A reconstruction of the star formation histories in various structures of M31 (Brown et al. 2006). *(a-c):* Radial velocities obtained with Keck for fields in the inner halo (11 kpc on the minor axis), tidal debris stream (20 kpc off-axis), and outer disk (25 kpc on the major axis), with M31 systemic velocity indicated (*dotted line*). *(d-f):* CMDs in these structures, constructed from *HST* images reaching *V*~30 mag, with a ridge line of the globular cluster 47 Tuc (white *curve*) shown for comparison. *(g-i):* Star formation history in each field, with the area of the circles proportional to the weight in the fit. The inner halo and tidal stream each show a similar history of extended star formation, due to the debris from the stream polluting the inner halo. The outer disk has a population similar to that in the thick disk of the solar neighborhood.

their star formation histories, but also the types of galaxies that were hierarchically assembled to construct the galaxies we see today. Despite the enormous successes of the cold dark matter (CDM) paradigm, CDM predicts that giant galaxies such as the Milky Way and M31 should be surrounded by many more dwarf galaxies than actually observed (e.g., Moore et al. 1999). As one way of solving the missing satellite problem, theorists have suggested that most dark matter sub-halos form few or no stars, due to the reionization of the universe (e.g., Tumlinson 2010; Bovill & Ricotti 2009). The discovery of tidally disrupted satellites around the Milky Way (e.g., Sgr dwarf; Ibata et al. 1994) and M31 (e.g., the giant stellar stream; Ibata et al. 2001) rekindled searches for faint or disrupted satellites in the Local Group that would possibly account for these missing satellites. Large surveys such as the Sloan Digital Sky Survey have discovered many new members of the Milky Way (e.g., Willman et al. 2005; Zucker et al. 2006) and M31 (e.g., Zucker et al. 2007; Majewski et al. 2007) systems, including the new class of ultra-faint dwarf galaxies. Recent *HST* observations of the ultra-faint dwarfs have found they are the only known galaxies comprised solely of ancient stars (> 13 Gyr old), implying their star formation histories were truncated by reionization, and lending credence to the idea that most dark matter sub-halos remain dark (Brown et al. 2012). However, no surveys will ever find the satellites that were already dispersed during hierarchical assembly. Insight into these objects must come from analysis of the field populations in the giant galaxies of today. Indeed, the population in the inner halo of M31 has been tied to a specific merger event that has not yet completed, as described above.

Methodology

The best tool for the reconstruction of star formation histories in nearby galaxies is photometry reaching dwarf stars on the main sequence. The color and luminosity of the main sequence turnoff and subgiant branch are very sensitive to both metallicity and age, while the color of the RGB is much more sensitive to metallicity than age. Spectroscopy of the bright giants can provide additional metallicity constraints (total metallicity, alpha enhancement, etc.) and kinematic information. With a CMD that includes both the bright giant stars and faint dwarf stars, one can disentangle the effects of age and metallicity to obtain the detailed distribution of these parameters in a stellar population (Fig. 2). A CMD that achieves a signal-to-noise ratio (SNR) of 5 at a point ~0.5 mag below the oldest main sequence turnoff in a population allows the reconstruction of the star formation history with age bins of ~1 Gyr over the entire lifetime of a galaxy, and metallicity bins of ~0.2 dex over the full range of abundances. A solar analog (absolute M_V~5 mag) is a familiar and approximate reference point for the depth that must be reached. The fitting of such CMDs was originally restricted to Galactic star clusters (e.g., Sandage 1953), but over time the fitting of CMDs has expanded to cover composite populations, first in Galactic satellites but eventually throughout the Local Group (e.g., Tosi et al. 1991; Gallart et al. 1999; Holtzman et al. 1999; Harris & Zaritsky 2001; Dolphin 2002; Brown et al. 2006, 2012; Cole et al. 2007).

For background-limited observations with a diffraction-limited telescope, the distance at which one can obtain photometry of faint stars is linearly proportional to the aperture diameter, assuming all other parameters are held fixed (bandpass, exposure time, SNR, instrument performance, etc.). This is true in both sparse and crowding-limited regions. In M31, *HST* can obtain

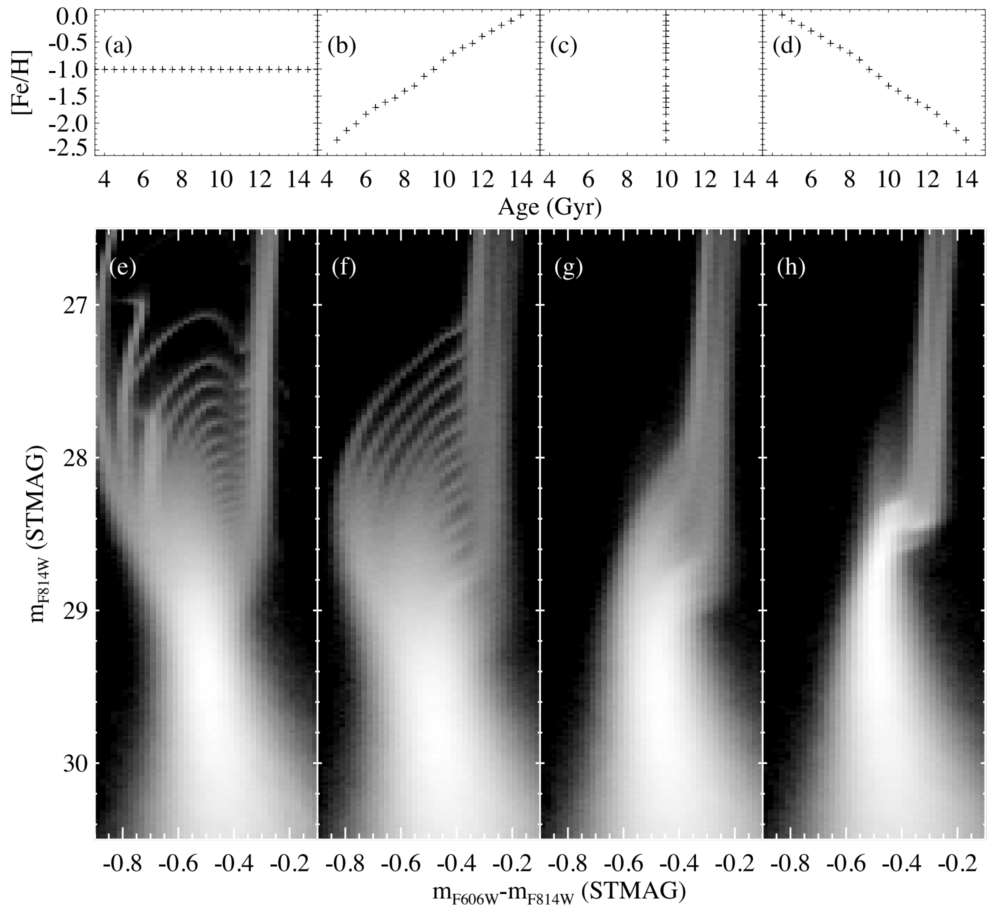


Fig. 2 - *Top panels:* Four hypothetical populations of stars. In each population, the stars are equally distributed among 20 isochrones distinct in age and metallicity. *Bottom panels:* Model CMDs for these hypothetical populations, with the observational errors of observations obtained in the M31 halo using *HST* (Brown et al. 2006). Because the main sequence turnoff, subgiant branch, and red giant branch all respond differently to changes in age and metallicity, a CMD that includes both the faint dwarfs and bright giants in a population breaks the age-metallicity degeneracy that would be present in observations of stars in a single evolutionary stage.

photometry of faint main sequence stars in regions where the surface brightness is roughly 26 V mag arcsec^{-2} or fainter. This brightness falls at ~10 kpc on the minor axis and ~25 kpc on the major axis; the interior is currently unavailable to such probes. Although the field cannot be too crowded, it cannot be too sparse, either, because an accurate star formation history in a complex population requires a CMD of ~10,000 stars (for age bins of ~1 Gyr, metallicity bins of ~0.2 dex, and sensitivity to sub-populations at the ~20% level). To do analogous work in a galaxy 10 times further away than M31, we need a telescope with an aperture that is 10 times larger than *HST*. The stars are 100 times fainter but we have 100 times the collecting area, so we get the same signal. The sky background is 100 times brighter (per unit area on the sky, due to the larger collecting area), but the area of each resolution element is 100 times smaller, so the sky signal within a resolution element stays the same. Thus, the SNR is the same for a given observing

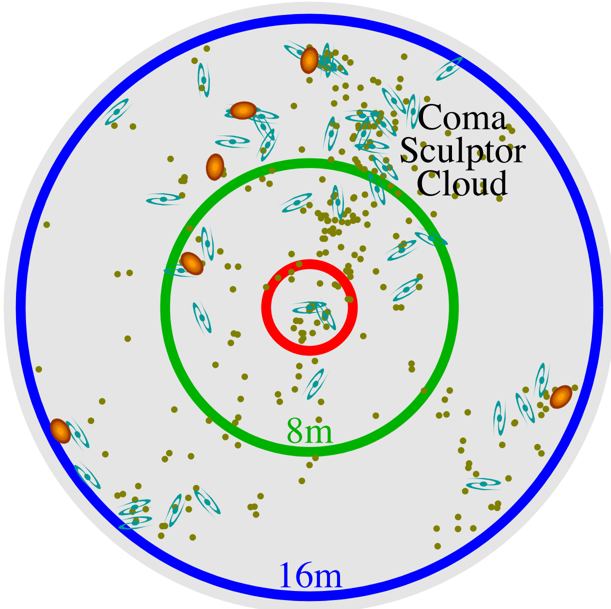


Fig. 3 - Giant spirals (blue symbols), giant ellipticals (red symbols), and dwarfs (brown symbols) within 12 Mpc of the Milky Way (center), deprojected to show actual distances. Concentric circles indicate where space observatories can obtain SNR=5 photometry of a solar analog star with 100 hours of observations split between two optical bands, thus obtaining the star formation history. The observatories indicated are *HST* (red circle), *ATLAST* 8m (green circle), and *ATLAST* 16m (blue circle).

time. Surface brightness is conserved - a given patch of stars is in an area 100 times smaller, but the stars are 100 times fainter and we are putting 100 times more resolution elements there. If the larger telescope has the same field of view as the smaller telescope, the larger telescope will have the advantage of sampling more physical real estate in the more distant galaxy. Furthermore, we are comparing here the performance of differently sized observatories at their distant limits, but the larger telescope provides enormous advantages in nearby galaxies that are within reach of both. The larger telescope can not only probe more crowded regions (instead of the faint outskirts currently accessible to *HST*) but can also survey much more efficiently, because the exposure time to obtain background-limited photometry of stars at a fixed distance is inversely proportional to the fourth power of aperture size.

Future Capabilities Needed

With an observatory similar to *HST* having an aperture in the 8 to 16 meter range, we can finally explore the full range of galaxy types and the variety of their structures, because the reach of such a telescope extends well beyond our rural Local Group into the more cosmopolitan Coma Sculptor Cloud (Fig. 3). The *Advanced Technology Large Aperture Space Telescope (ATLAST)* would be such a telescope, and it is currently the subject of a NASA-funded study led by M. Postman. An 8 meter aperture is needed to reach at least one giant elliptical, while a 16 meter aperture is needed to reach a significant sample of both giant ellipticals and giant spirals (Fig. 4).

In the current era, there is a synergy between *HST* and large ground telescopes like Keck. *HST* imaging can provide accurate photometry of faint dwarf stars at V~30 mag in Local Group galaxies, while Keck spectroscopy can provide radial velocities for bright giant stars at V~22 mag in the same populations, providing important kinematical context (e.g., see Fig. 1). The James Webb Space Telscope (*JWST*) will extend our reach for this work to galaxies 50% more distant than those available to *HST*. In the era of a 16m *ATLAST* and a 30m ground telescope (e.g., TMT), this synergy will move outward to much more distant galaxies, with *ATLAST* obtaining photometry of V~35 mag dwarf stars in the Coma Sculptor Cloud and TMT obtaining kinematics of bright giants in the same populations. These faint dwarf stars are effectively impossible with TMT, requiring Gigaseconds of integration even for an isolated star. A space platform is required for this type of work, because one needs stable high-precision photometry for thousands of stars in large crowded large fields with faint sky backgrounds, and this photometry must be accurate for stars spanning a large dynamic range (~L_{Sun} to 10,000 times brighter).

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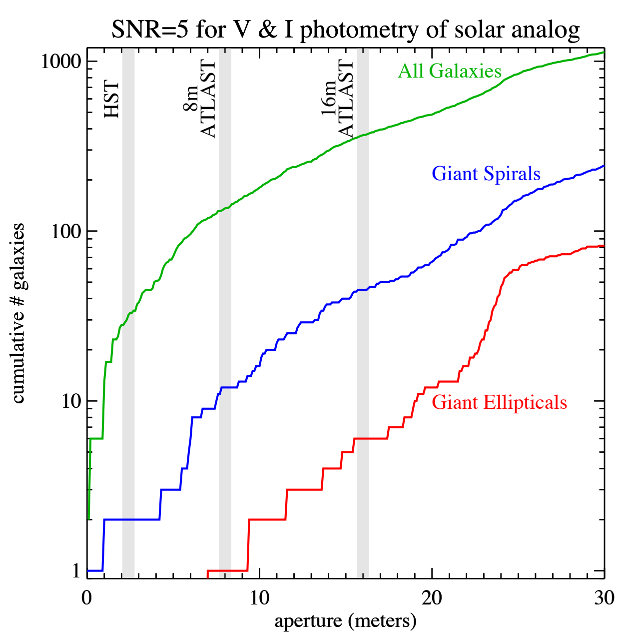

Fig. 4 - The cumulative number of galaxies where space telescopes can obtain the detailed star formation history, as a function of aperture diameter, assuming 100 hours of observations split between the V & I bands. The star formation history can be measured anywhere one can obtain SNR=5 photometry of solar analog stars. Representative observatories are indicated by grey lines. To measure the star formation history in a significant sample of giant elliptical galaxies, one needs at least a 16m space telescope.

Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies

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Abstract

Star formation plays a central role in the evolution of galaxies and of the Universe as a whole. Studies of star-forming regions in the local universe have shown that star formation typically occurs in a clustered fashion. Building a coherent picture of how star clusters form and evolve is therefore critical to our overall understanding of the star formation process. Most clusters disrupt after they form, thus contributing to the field star population. However, the most massive and dense clusters remain bound and survive for a Hubble time. These globular clusters provide unique observational probes of the formation history of their host galaxies. In particular, the age and metallicity can be determined for each globular cluster individually, allowing the *distribution* of ages and metallicities within host galaxies to be constrained.

We show how space-based UV-to-Near-IR imaging covering a wide field of view ($\gtrsim 20'$ per axis) and deep UV/Optical multi-object spectroscopy of globular cluster systems in nearby galaxies would allow one to place important new constraints on the formation history of early-type galaxies and their structural subcomponents (e.g., bulge, halo).

1 Globular Clusters as Fossil Records of the Formation History of Galaxies

Infrared studies of star formation within molecular clouds have shown that stars typically form in clusters or associations with initial masses $\mathcal{M}_{\rm cl,\,0}$ in the range $10^2 - 10^8\ M_\odot$ (e.g., Lada & Lada 2003; Portegies Zwart et al. 2010). While most star clusters with $\mathcal{M}_{\rm cl,\,0} \lesssim 10^4\ M_\odot$ are thought to disrupt and disperse into the field population of galaxies within a few Gyr, the surviving massive GCs constitute luminous compact sources that can be observed out to distances of several tens of megaparsecs. Furthermore, star clusters represent the best known approximations of a "simple stellar population", i.e., a coeval population of stars with a single metallicity[1], whereas the field stars in galaxies typically constitute a mixture of populations. Thus, studies of globular cluster systems can constrain the *distribution* of stellar ages and metallicities whereas measurements of the integrated light of galaxies can only provide luminosity-weighted averages of these key quantities. Consequently, globular clusters represent invaluable probes of the star formation rate and chemical enrichment occurring during the main star formation epochs within their host galaxy's assembly history (see, e.g., reviews of Ashman & Zepf 1998; Brodie & Strader 2006).

The study of extragalactic globular clusters was revolutionized by the Hubble Space Telescope (HST). The main reason for this is that the size of globular clusters is well-matched to diffraction-limited optical imaging with a 2-m class telescope: a typical globular cluster half-light radius of ~ 3 pc at a distance of 15 Mpc corresponds to $\sim 0\farcs05$ on the sky, which is roughly the diffraction limit (and detector pixel size) in the V band for HST. This yields very high quality photometry of globular clusters relative to ground-based optical imaging by beating down the high galaxy surface brightness in the central regions of galaxies. Furthermore, it also allows robust measurements of globular cluster radii, and hence of their dynamical status.

Notwithstanding the important progress that HST imaging has facilitated in this field, there is one critical property of globular cluster systems that HST imaging *cannot* address well. Globular cluster systems around massive early-type galaxies extend far into the galaxy halos, covering several tens of arcminutes on the sky (e.g., Goudfrooij et al. 2001; Rhode & Zepf 2001, 2004; Zepf 2005), while HST images only cover the central $\sim 3\farcm3 \times 3\farcm3$. This is illustrated in Figure 1. Obviously, *wide fields of view* ($\gtrsim 20'$ per axis) are required to accurately determine total properties of globular cluster systems (e.g., total numbers of clusters per unit galaxy luminosity, color or metallicity distributions, trends with galactocentric distance). Furthermore, the faint outer halos of galaxies are thought to hold unique clues regarding the early assembly history of galaxies, and bright globular clusters constitute one of the very few probes that can be studied in these environments. In the following we highlight a few key science questions in this growing field for which new space-based UV/Optical instrumentation can be expected to yield major steps forward in our understanding of the formation and evolution of galaxies.

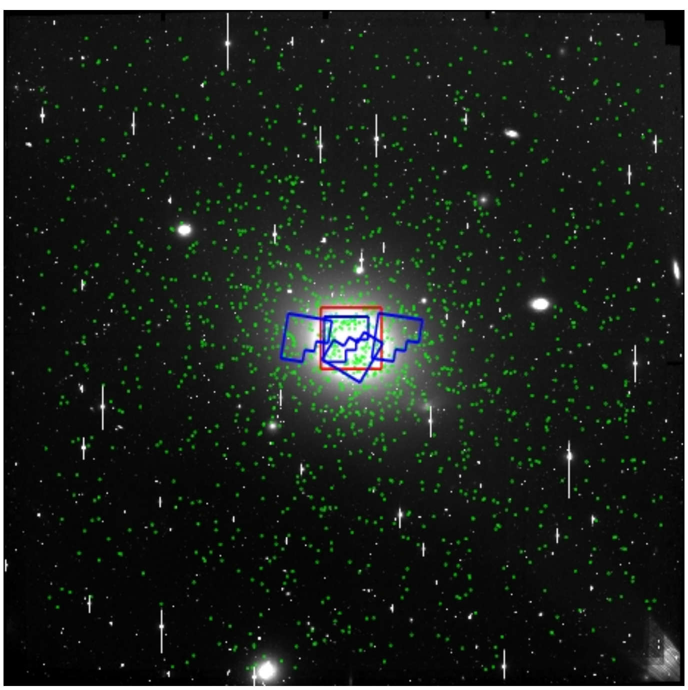

Figure 1. R-band KPNO 4-m/MOSAIC image of the giant elliptical galaxy NGC 4472 in the Virgo cluster of galaxies, covering a $36' \times 36'$ field of view. Footprints of available HST/ACS and HST/WFPC2 images are drawn in red and blue, respectively. Globular cluster candidates from Rhode & Zepf (2001) are indicated as green dots. Note the small fraction of globular cluster candidates covered by HST images, implying the need for large and uncertain extrapolations when trying to extend conclusions from the HST studies to the full systems of globular clusters. Figure taken from Zepf (2005).

[1]Massive star clusters in the Milky Way host secondary populations with varying relative light-element abundances (e.g., Gratton et al. 2012). However, the effect of these variations to optical and near-IR colors is negligible (Sbordone et al. 2011).

2 New Constraints on the History of Star Formation and Chemical Enrichment of Early-Type Galaxies

A key discovery of HST studies of globular cluster systems of luminous galaxies was that their optical color distributions are typically bimodal (e.g., Whitmore et al. 1995; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2006). Figure 2 shows an example. Follow-up spectroscopy of bright globular clusters using 10-m-class telescopes has indicated that both "blue" and "red" populations are typically old (age $\gtrsim$ 8 Gyr), implying that the color bimodality is mainly due to differences in metallicity (e.g., Cohen et al. 2003; Puzia et al. 2005). In broad terms, the metal-rich globular cluster population features colors, metallicities, radial distributions, and kinematics that are similar to those of the spheroidal ("bulge") component of early-type galaxies. In contrast, the metal-poor globular cluster population has a much more radially extended distribution, and is likely physically associated with metal-poor stellar halos such as those found around nearby galaxies (e.g., Bassino et al. 2006; Goudfrooij et al. 2007; Peng et al. 2008).

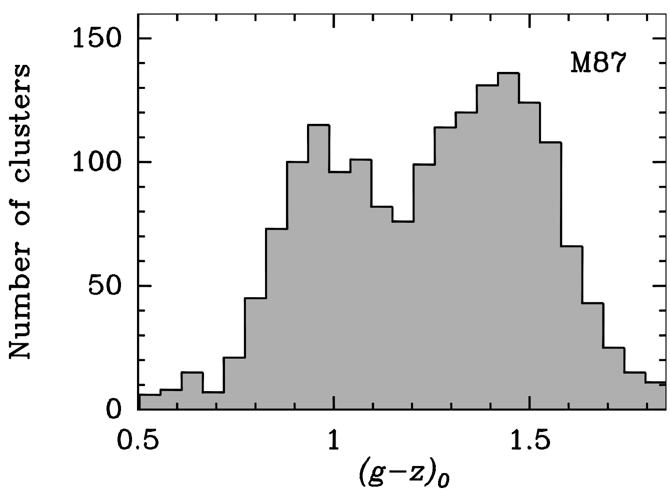

Figure 2. $g-z$ color distribution of globular clusters in the massive elliptical galaxy M87 from Peng et al. (2006). Note the obvious color bimodality, which has been confirmed to be mainly due to differences in metallicity, and which is common among massive early-type galaxies in the local universe.

The bimodality in optical colors of globular clusters constitutes one of the clearest signs that star formation in luminous early-type galaxies must have been episodic. However, we emphasize that the optical color distributions do not significantly constrain *when* these events occurred, or in what order. This is because optical colors alone cannot generally distinguish between different combinations of age and metallicity (the "age-metallicity degeneracy"). A general understanding of the age and metallicity distributions of globular cluster systems requires braking this degeneracy. There are two primary and complementary ways to do this, described below:

1. **The addition of near-infrared photometry to optical data**. The main power of this method (using color-color diagrams) is the ability to identify age differences (of order $\gtrsim$ 25% for high-quality data), due to the fact that near-IR colors are primarily sensitive to metallicity while optical colors are sensitive to both age and metallicity. This approach resulted in the identification of substantial populations of intermediate-age metal-rich globular clusters in several early-type galaxies (Goudfrooij et al. 2001; Puzia et al. 2002; Hempel et al. 2007; Georgiev et al. 2012). The current limitation of this method is twofold. While HST has a powerful near-IR channel in its WFC3 instrument, its use is limited to the *innermost regions* of nearby galaxies due to its relatively small footprint of $\sim 2' \times 2'$ (cf. Figure 1 above). The NIRCam instrument to be installed on the 6.5-m James Webb Space Telescope (JWST) will reach 2 mag fainter than HST in a given integration time, but its footprint is similarly small. Conversely, while near-IR imaging instruments with reasonably large fields of view are starting to become available on large ground-based telescopes (e.g., $7\farcm5 \times 7\farcm5$ for HAWK-I on

the VLT), contamination of globular cluster candidate samples by compact background galaxies is a major concern for ground-based spatial resolution (see, e.g., Rhode & Zepf 2001). As demonstrated by HST, imaging at $\sim 0\farcs1$ resolution effectively eliminates this concern due to the marginally resolved nature of globular clusters (cf. Section 1). Thus, the study of galaxy formation and evolution by means of accurate globular cluster photometry will benefit tremendously from space-based wide-field UV/Optical imaging. A relatively simple multi-chip UV/optical camera installed on one of the two 2.4-m telescopes recently donated to NASA by the National Reconnaissance Office would be ideal for this (and many other) purpose(s). Their fast (f/1.2) primary mirror could easily yield a useful field of view of hundreds of square arcminutes per exposure at a resolution of $\sim 0\farcs1$, providing accurate photometry of virtually *all* globular clusters associated with nearby galaxies with very little contamination. Along with a relatively standard suite of broad-band and narrow-band filters from the near-UV through the near-IR, such an instrument would place important constraints on the formation and assembly history of massive early-type galaxies, particularly in their outer regions for which there currently are few other constraints.

2. **Optical multi-object spectroscopy with large telescopes**. The main strength of this technique lies in the presence of intrinsically strong absorption lines of several key elements in the optical region, which facilitates accurate determinations of overall metallicities and element abundance ratios that can be used to infer typical timescales of star formation (e.g., Puzia et al. 2005, 2006). However, this technique is currently only available from the ground and is therefore significantly hampered by the high surface brightness of the diffuse light of the inner regions of the host galaxies. In practice, this limits the application of this technique currently to mainly the *outer regions* of galaxies. This has caused a general lack of crucial spectroscopic information for the metal-rich globular clusters, which are located mainly in the inner regions. While future developments in the area of adaptive optics systems on large telescopes will enable high spatial resolution imaging and spectroscopy from the ground, they will do so only over a small ($\lesssim 1'$) field of view which is not useful for spectroscopy of extragalactic star clusters. This science would however advance dramatically with a 8-m class UV/Optical space-based telescope (such as the concepts proposed for ATLAST) equipped with a multi-object spectrograph with field of view of several arcmin per axis. Note that radial velocities resulting from such globular cluster spectra will also provide important kinematical probes in the outskirts of galaxies (where the diffuse light is too faint to give useful information).

3 From Star Clusters to the Field Star Population in Galaxies

Star clusters begin disrupting (losing mass) as soon as they are formed. Understanding how they do so as a function of cluster mass, time, and environment is key to many questions in the study of star clusters and their relation to galaxies. A main observable in this context is the star cluster mass function. HST studies have shown that among young cluster systems in star-forming galaxies, the mass function is well approximated by a power law ($\psi(M) \propto M^{\alpha}$ with $\alpha \simeq -2$, see, e.g., Fall et al. 2009 and references therein). On the other hand, cluster mass functions in ancient galaxies such as giant early-type galaxies and our Galaxy show a log-normal shape (e.g., Jordán et al. 2007). This stark difference (illustrated in Figure 3) is most likely due to dynamical evolution of the star cluster system. It is however not yet clear how this important process happens in detail, and the recent literature contains many different theoretical models and observational conclusions regarding this transition. Being able to distinguish between the various ideas will have relevant implications as to how, and to what extent, the field star population in galaxies is built up over time from disrupting star clusters.

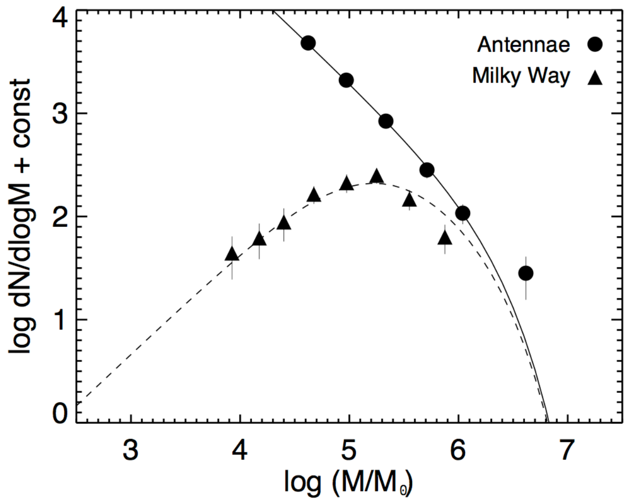

Figure 3. A comparison of the mass function of the young star cluster system of the Antennae galaxies (Fall et al. 2009) with that of the globular cluster mass function in the Milky Way. The stark difference between these mass functions illustrates the important effect of dynamical evolution of star clusters over time.

As to the early stages of the cluster disruption process, the number of clusters per unit log(age) in several star-forming galaxies appears to decline starting at very young ages, suggesting that many clusters dissolve easily (e.g., Whitmore et al. 2007; Fall & Chandar 2012). It is however not yet clear which mechanism is most responsible for this rapid dissolution. Longer-term mass loss of star clusters over a Hubble time is likely responsible for the very different shapes observed for young and ancient star cluster systems (cf. above). However, the disruption processes must also account for the observation that the mass function of old globular clusters appears to be similar among virtually all galaxies. Several different scenarios have been proposed to explain this observation, each advocating different disruption mechanisms that act on different time scales (e.g., Vesperini & Zepf 2003; Parmentier et al. 2008; McLaughlin & Fall 2008; Gieles et al. 2011).

It is likely that the variety of proposed explanations for the difference between mass functions of young and old star cluster systems is caused in large part by the small footprint of HST images on the sky. In the central few kpc of massive galaxies covered by HST images, the strong tidal field imposes a relatively small range of mass densities on globular clusters in order for them to survive tidal shocks for several Gyr (see, e.g., Gnedin 1997; Goudfrooij 2012). This means that the current distribution of globular cluster sizes and mass densities (derived from HST data) has no memory of the physical conditions occurring when the clusters were formed, or even when they may have been accreted from dwarf galaxies (if they were). This situation is quite different in the outer regions of galaxies, where the tidal limit imposed by the galaxy potential on star cluster sizes is much larger and observed star cluster sizes *do* constrain the conditions occurring when the star clusters were formed or accreted (e.g., Madrid et al. 2012). However, we simply do not have adequate size information for star clusters in the outer regions of massive galaxies at this time, and HST is not a suitable facility in this context.

The determination of accurate ages for globular clusters at different distances from the galaxy centers using space-based wide-field optical and near-IR photometry and optical multi-object spectroscopy (cf. Section 2 above) will also yield important information to sort out the relevance of various cluster disruption mechanisms (e.g., Goudfrooij 2012).

In summary, accurate, deep cluster mass functions and size information for the *full spatial extent of star cluster systems* will be key to our understanding of dynamical evolution of star clusters and the nature of the field star component in massive galaxies. Similar to the aforementioned study of the star formation history of galaxies using globular cluster photometry (cf. Section 2), this study requires wide-field optical imaging with spatial resolution of order $0\farcs1$ for which one of the 2.4-m space telescopes donated to NASA by the National Reconnaissance Office would be a very well-suited platform.

4 Concluding Remarks

The increasing realization that the study of star clusters has direct relevance for the basic processes involved in how galaxies assemble and evolve over time has placed this field at the forefront of extragalactic research in recent years. We have described two fundamental questions that are of central importance in star cluster research, and identified two types of future UV/Optical space telescope facilities that would enable significant breakthroughs in these areas, providing important new constraints for galaxy formation, assembly, and evolution. These two types of facilities are:

1. A wide-field (of order $20' \times 20'$), multi-detector imaging camera on a moderate-size space telescope with small focal ratio. One of the two f/1.2, 2.4-m space telescopes recently donated to NASA by the National Reconnaissance Office would be very well-suited to host such an instrument.
2. A 8-m class space telescope that includes a multi-object spectrograph that supports observations of $\gtrsim 100$ targets per exposure, covering a field of view of several arcmin per axis. The concepts proposed for ATLAST seem compatible with these requirements.

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Response to Solicitation NNH12ZDA008L: Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts

The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies

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Abstract

Models of galaxy formation and evolution are only as reliable as our knowledge of the individual stars responsible for the light we detect. From the prescriptions for stellar feedback, to numerical simulations, to the interpretation of galaxy colors and spectra, galaxy evolution research depends at its core on reliable star formation and evolution models. These models are calibrated using observations of resolved stellar populations in a wide range of environments. Studies of stellar populations in the UV have made great strides in the past decade with the *GALEX* UV surveys and the UV-sensitive WFC3 camera on *HST*. With the phenomenal data that these instruments have provided, we have learned surprising UV properties of the stellar populations of galaxies and star clusters. While these observations have certainly shed light on the evolution of stars and star clusters, the picture is still far from complete. To fully understand the processes that shape star formation of clusters and OB associations in galaxies with a range of masses, metallicities, and gas content will require the next generation of UV telescopes and instrumentation. To make significant progress, goals for this future instrumentation will need to include improved spatial resolution to resolve individual stars in crowded extragalactic environments and a larger field of view to cover nearby galaxies with fewer pointings. Future observations will then be able to produce the required libraries of resolved stars in carefully selected UV bands to reveal the phyical properties of the stars and properly account for dust extinction. We will detail the instrument requirements for making the necessary observations.

Introduction

In this response, we will discuss the scientific necessity for understanding the details of UV emission from the individual stars that contribute to the integrated light of galaxies and star clusters. Nearly all of the trillions of galaxies in the universe can only be detected through their integrated starlight, even in *HST* (e.g., Coe et al., 2006) or simulated *JWST* images.[1] These faint blobs of light are the luminosity-weighted average emission from the stars that make up those galaxies. To interpret this light therefore requires reliable, well-calibrated models of stars, especially the brightest stars that dominate the luminosity-weighted average. Such models rely on large libraries of photometry and spectra of individual stars (e.g. Bruzual & Charlot, 2003). Such libraries are improving, largely due to *HST*. However, because of the limitations of available telescopes and instruments, the libraries only sample a small fraction of star forming environments, and they contain little UV data. Such incomplete libraries render our interpretation of light from all distant galaxies highly uncertain.

At high-redshift, when the cosmic star formation rate was at its peak ($2<z<4$, e.g., Reddy et al., 2008), the optical light we observe is largely stellar light redshifted from the UV. For the highest redshift galaxies observed ($z\sim8$; Bouwens et al., 2010), the only light we detect is UV emission redshifted to the near infrared. At these redshifts, the UV emission is dominated by young, massive stars. Constraining the physical properties (temperature, mass, age) of these stars is of great interest not only for measuring their contribution to the total light emission from the galaxy, but also for constraining their effects on the surrounding interstellar, and potentially intergalactic, medium.

In addition to the importance of UV observations for measuring the effects of star formation and massive stars on the evolution of galaxies, UV observations have also proven incredibly sensitive to the evolution of old, low-mass stars. In particular, with resolved UV photometry of old stellar populations, we have begun to constrain the evolution of stars through the hot horizontal branch, including short-lived, UV-bright phases of evolution that can significantly affect the UV luminosity of galaxies and are relevant to the yield of chemical elements. Furthermore, this UV-sensitivity has proven itself capable of constraining generations of stars at very old ages (>10 Gyr), something that was not possible with optical data alone.

In nearby galaxies and star clusters, the UV flux can be resolved into individual stars. An example of this resolving power is shown in Figure 1. The two panels show the same region in M31 as observed by *GALEX* (left) and UVIS on *HST* (right). With the high-resolution *HST* image, it is clear that the *GALEX* emission comes from individual hot stars. These stars are excellent analogs of the stars responsible for the UV light we observe from more distant galaxies and star clusters, and therefore offer our most precise constraints on and reliable tests of the mass and age distributions inferred from the light observed in distant systems.

The fact that most UV emission from galaxies is from stars may not be surprising, but unfortunately, very few of these stars have actually been studied in the UV. The lack of observational constraints makes the interpretation of integrated light difficult. We will now discuss the advantages of UV observations of young and old stellar populations in detail, showing that resolving individual stars in the UV is crucial for the advancement of near-field, as well as, high-z cosmology.

Massive Stars

The evolution of galaxies is strongly affected by the process of star formation. During their

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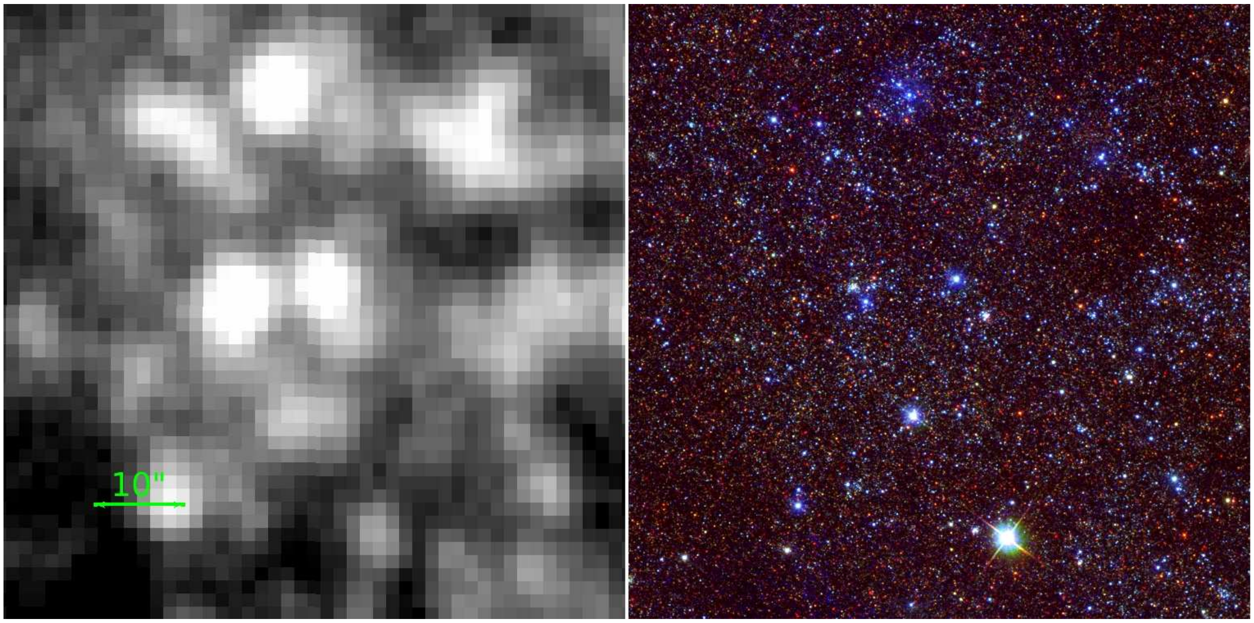

Figure 1: *Left: GALEX* NUV image of a UV bright portion of the M31 disk. *Right: HST* UVIS image of the same region (blue=UV, green=V, red=I). The UV emission detected by *GALEX* clearly originates from bright blue stars.

short lifetimes, high-mass stars produce ionizing radiation, powerful stellar winds, supernova explosions, and heavy elements. All of these processes contribute significantly to the movement, temperature, pressure, and chemistry of the gas in the galaxy potential. The fate of this gas — whether it escapes the galaxy, forms a hot halo, or cools and forms more stars — fundamentally shapes the evolution of the galaxy.

Massive stars provide most of the rest-frame UV radiation we observe, which is then used to infer fundamental properties, such as the initial mass function (IMF) and star formation rates. The utility of UV measurements is crucial, but must be calibrated using large samples of individual massive stars in a variety of environments.

The UV as a Probe of Star Formation

UV flux has long been considered an indicator for the star formation rate in galaxies (Salim et al., 2007). These rates require reliable models of the UV flux from massive stars and proper dust-extinction corrections. However, because of the scant available UV data of massive stars, currently limited to the Milky Way and Magellanic Clouds, these models suffer from significant deficiencies. When the models are tested with measurements of resolved stars in other nearby galaxies, significant systematic errors appear (see Figure 2). Not only is too much UV flux predicted, it is also bluer than what is actually observed.

The resulting errors in predicted UV fluxes point to clear deficiencies in the current models of massive stars, which have far-reaching impacts on the interpretation of the light from distant galaxies. A comprehensive library of massive star UV fluxes covering as many galaxy types as possible is necessary to provide the best calibration of these models. Such a library would be well-served to include high SFR galaxies like NGC 253 and M82, as well as all nearby dwarf galaxies. Such observations require higher spatial resolution and UV sensitivity than *HST*.

Distinguishing Temperature and Dust Effects

Only with UV observations of individual stars is it possible to separate the effects of

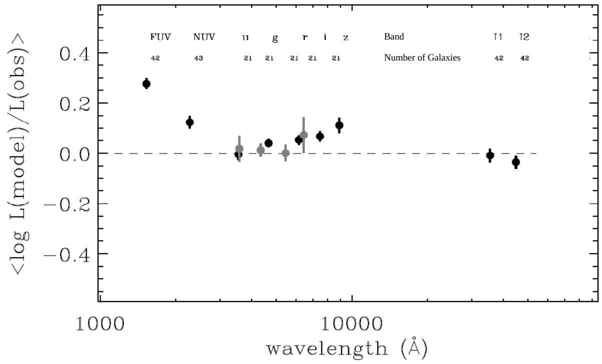

Figure 2: Residuals of observed vs. modeled SEDs for star-forming dwarf galaxies (B. Johnson et al. in preparation). Models derived from star formation rates determined from *HST* resolved stellar photometry do an excellent job of predicting the integrated fluxes in the optical and stellar-dominated NIR bands, but fail dramatically in the UV.

temperature and dust reddening, allowing reliable measurements of stellar temperature and radii. This ability is shown in Romaniello et al. (2002) and more recently in Bianchi & Efremova (2006); Bianchi et al. (2011, 2012) The spectral energy distributions (SEDs) of massive hot stars are indistinguishable in the optical data alone. However, when UV data are included in the SED, a reliable temperature and extinction can be measured (and luminosity, mass, and age inferred).

Such studies of resolved young stellar populations in nearby environments allow us to quantify the star formation process. For example, we can measure the spatial scales and hierarchical clustering of young stars, revealing the effects of dynamical evolution. An example of this from the *HST* M31 multicycle treasury program (Dalcanton et al., 2012) is shown in Figure 3, where the temperatures and radii of thousands of stars measured by this technique are shown spatially for a section of M31. Hotter (younger) stars are more spatially clustered.

Finally, the extinction measurements for each star probes the structure of the dust cloud, quantifying the dust distribution and the reprocessing of UV light from massive stars into IR light from warm dust. These quantitative constraints on the massive star content are only possible with wide-field ($>10'$), high spatial resolution ($<0.1''$) imaging in the UV, which provide the necessary data for a large enough number of stars over a sufficiently large portion of the galaxy to probe environmental effects on the star-formation process.

The Initial Mass Function

Future UV observations of extragalactic massive stars are critical to our measurement of one of the most fundamental relations in astrophysics, the initial mass function (IMF). The IMF provides the foundation for the interpretation of photometry and spectroscopy of galaxies. For example, one must assume an IMF to calculate the amount of stellar mass that is represented by the UV light observed in from a galaxy. Unfortunately the high-mass end of the IMF, which has the most impact on the interpretation of the luminosity-weighted fluxes we observe, remains highly uncertain (Kroupa, 2001; Bastian et al., 2010, Weisz et al. ApJ, submitted). In fact, it is not yet clear if the IMF is a strong function of environmental properties, such as metallicity and star formation rate, or is universal (Bastian et al., 2010).

The lack of knowledge about the high mass IMF is largely due to a lack precise mass measurements of high-mass stars, and the most precise masses are provided by UV data. Reliable temperatures, as measured using the methods described above, can be converted to luminosities and masses using well-constrained scaling relations. These masses can then be analyzed to constrain the high-mass IMF. With our copious *HST* data on M31, we will likely gain knowledge of the IMF *in this one system.* We will need data in more, and different, systems to put tight constraints on universality.

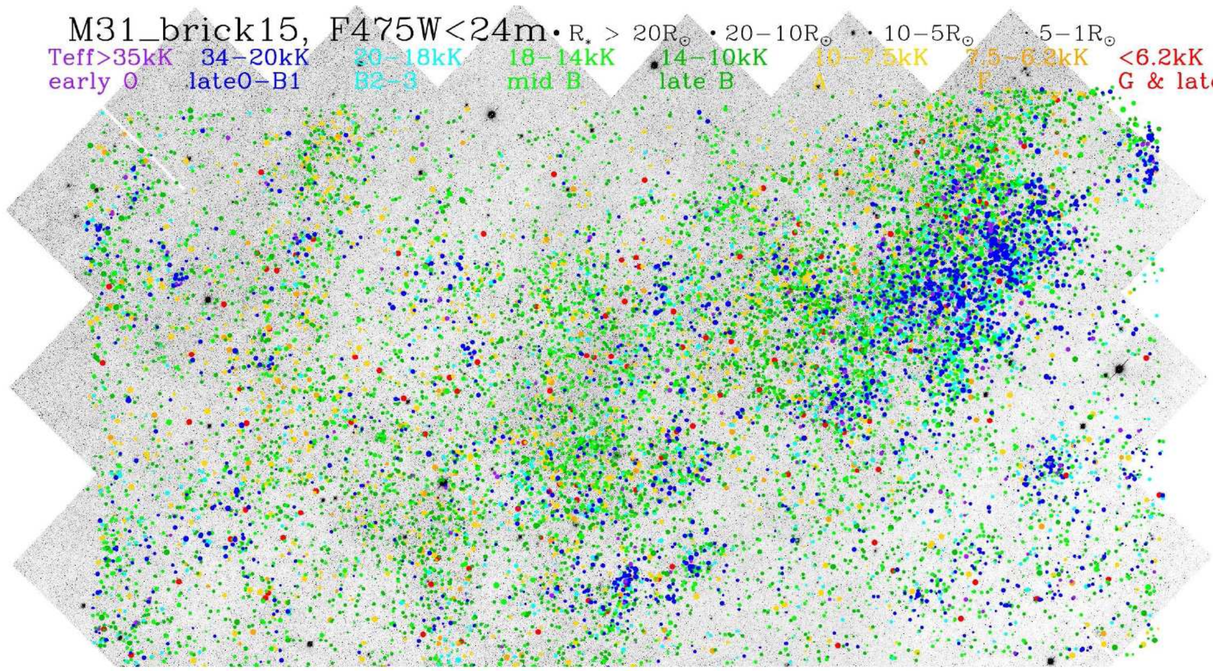

Figure 3: The locations of massive stars over a $12' \times 6'$ area of the M31 disk. Colors indicate temperature; point size indicates radius (Bianchi et al., in preparation).

Low Mass Stars

Although massive stars are usually thought to be the only sources of UV emission, low-mass stars also evolve through UV-bright phases that can significantly affect the integrated UV flux. This issue goes back to the earliest UV observations ever made. The Orbiting Astronomical Observatory observed the bulge of M31 in the UV for the first time. The M31 bulge was expected to be UV faint because it is dominated by old stars. Instead, significant flux toward shorter wavelengths was detected (Code, 1969). M32, another old system, also shows such a UV-excess, along with many other non-star-forming early type galaxies (e.g Burstein et al., 1988).

Short-lived, UV-Bright Evolutionary Stages

Thanks to *HST*, we now have the ability to resolve some of the UV emission from the M31 bulge and M32 into individual stars (Brown et al., 2000; Rosenfield et al., 2012). The stars responsible for the bulk of the UV light from old populations are now known to be extreme horizontal branch (EHB) stars (O'Connell, 1999; Brown et al., 2000). However, we only cleanly resolve the bright end of the UV-bright populations in the M31 bulge and M32 with the current instrumentation. These brightest stars are the post-HB stars, not the much more numerous EHB stars responsible for the bulk of the UV flux, which cannot currently be probed directly.

Even without resolving the EHB population itself, progress has been made. For example, a correlation between EHB production and metal abundance is clear, both in galaxy samples (Burstein et al., 1988; Bureau et al., 2011) and within M31 (Rosenfield et al., 2012), providing constraints on evolution theories that produce these EHB stars. Furthermore, the UV-excess appears to decrease with redshift (Ree et al., 2007), consistent with its association with very old populations. A handful of these stars have been studied in detail in our Galaxy (Busso et al., 2005); however, detailed observations of a large sample will require the next generation UV telescope to have higher sensitivity and spatial resolution than *HST*.

Detailed Abundance Sensitivity

The UV spectral range is well-known to contain a very dense forest of features from metals and molecules. The number of features in the UV is so dense that the SEDs of metal-rich stars are redder due to "line-blanketing," a term used to describe the cumulative effect of many absorption features significantly depressing the broadband UV flux. Thus, the UV properties of stars are very sensitive to their abundance characteristics. *These spectral features cannot be observed through the Earth's atmosphere,* so that without UV capability in space, such areas of research will be completely lost. This sensitivity has allowed the UV to be used to separate multiple stellar populations in systems that traditionally have been considered single population systems: globular clusters.

For example, deep resolved UV stellar photometry of the globular cluster 47 Tuc reveals two separate sequences of stars corresponding to two generations, both ancient, but with differing chemistry. The first generation is nitrogen-poor, while the second is nitrogen-rich. Because the UV contains a strong nitrogen-sensitive absorption feature, the UV photometry easily separates the two previously-unidentified populations (Milone et al., 2012). The separation of the stars into their separate generations allows the robust measurement of the fraction of stars from each. In 47 Tuc, the second generation dominates everywhere in the cluster and is more centrally concentrated than the first.

These quantitative measurements of processes that occurred more than 12 Gyr ago were made possible by high spatial resolution, high sensitivity UV observations, and require a UV-sensitive telescope in space. 47 Tuc is one cluster among hundreds in our Galaxy, and those in our galaxy do not well sample a wide range of ages and metallicities. Performing such detailed studies on the younger and more metal-rich globular clusters in M31 (and some of the younger and lower metallicity clusters in M33) for example, would provide a significant leap forward in our understanding of the formation of globular clusters under more diverse conditions.

Technical Goals

We are currently barely capable of resolving the stars of interest in the Local Group (<1 Mpc). The limits are due to spatial resolution. At *HST* resolution, young stars in galaxies outside of the local group blend together, which does not allow us to measure the properties of the individual stars. Spatial resolution better than that of *HST* is therefore require to make measurements outside of the Local Group.

The next mission would fundamentally improve our available libraries of resolved stars if one of its goals were to resolve the stars of interest in the nearest galaxies with star formation rates comparable to those at high-redshift. These are NGC 253 (Engelbracht et al., 1998) and M82 (Telesco, 1988), at distances of $\sim$4 Mpc. A new regime in observational experiments can be reached with a diffraction limit roughly a factor of 4 better than that of *HST*, *i.e.*, an 8–10 meter UV/Optical space telescope.

Furthermore, field of view is of great importance. For example, the M31 multicycle treasury program will spend 828 orbits to map a large portion of the disk; this program could be completed in 8 orbits if the ACS and WFC3 fields of view were 100 times larger at the same spatial resolution. Such a prospect requires very large numbers of pixels and the ability to store and dump the very large images required. On the ground, cameras with more than 100$\times$ the current number of UVIS pixels are under construction (Gilmore et al., 2012), suggesting such a large increase in field of view may be possible for the next generation of space telescopes. Such an increase would boost the productivity of the observatory by two orders of magnitude.

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A Census of Local Group Ultraviolet Dust Extinction Curves

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Summary

Interstellar dust plays a central role in shaping the detailed structure of the interstellar medium, thus strongly influencing star formation and galaxy evolution. Ultraviolet extinction curves provide one of the main pillars of our understanding of interstellar dust while also being one of the limiting factors when interpreting observations of distant galaxies. Our observational picture of extinction curves is strongly biased to nearby regions in the Milky Way. However, the few extinction curves measured in the Magellanic Clouds show curves that are quite different from those seen in the Milky Way. We propose an observational program to obtain a census of ultraviolet dust extinction curves in the Local Group by measuring large, statistically significant samples of extinction curves in each Local Group galaxy. This program requires sensitive medium-band UV and blue-optical imaging and followup R $\sim$ 1000 spectroscopy of 1000's of sources. This census will, for the first time, provide a full census of dust and its variation with environment and galaxy type. It would simultaneously generate one of the largest ultraviolet spectral libraries ideal for a range of hot star studies. Such a census will revolutionize our understanding of the dependence of dust properties on local environment providing both an empirical description as well as strong constraints on dust grain and evolution models.

Background

Dust in the interstellar medium plays a central role in star formation and galaxy evolution. It helps shape the detailed structure of the interstellar medium (ISM), thereby directly influencing the process of star formation. It provides crucial shielding in molecular clouds and is the main formation site for molecular hydrogen. A thorough understanding of interstellar dust in galaxies in the local universe is needed to better understand the properties of dust itself as well as enable a clearer picture of star formation in galaxies.

The presence of dust is easiest to observe in the ultraviolet (UV), where it strongly absorbs and scatters photons, and in the infrared, where the absorbed energy is re-emitted through non-equilibrium (near- and mid-IR) and equilibrium (far-IR and submm) processes. The effects of dust on the UV (and optical/near-IR) spectrum of a background star is often

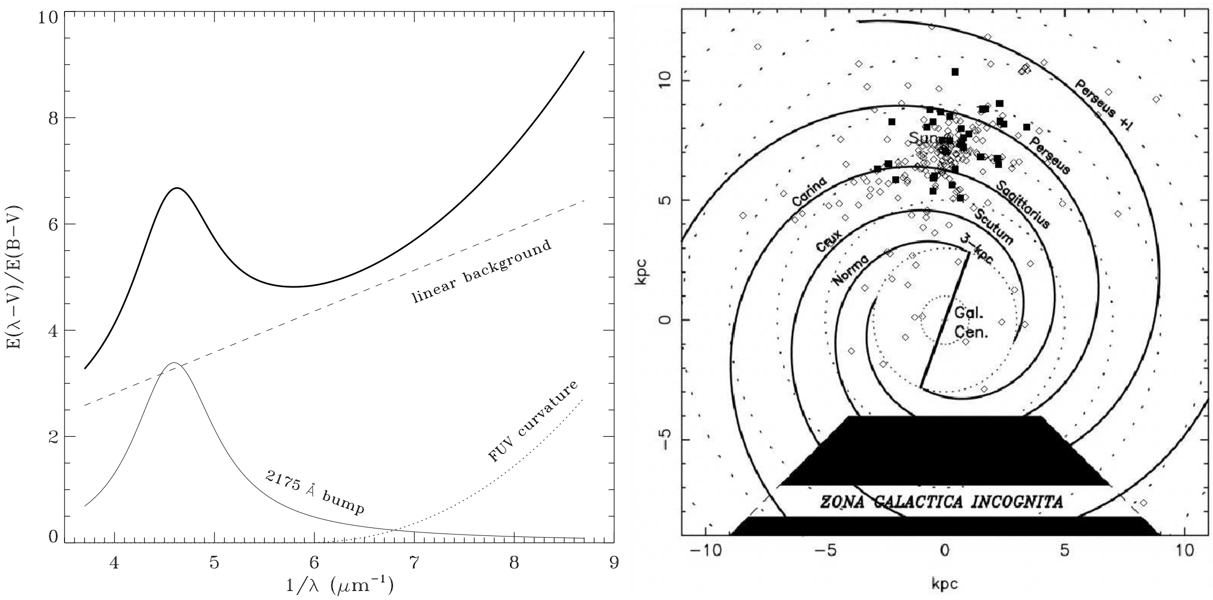

Figure 1: (a, left) All measured UV extinction curves can be decomposed into 3 components; a linear background, the 2175 Å bump, and a FUV curvature term. Figure from Fitzpatrick (1999). (b, right) The distribution of known Milky Way extinction curves is plotted projected onto the plane of the Galaxy. Figure from Valencic et al. (2004).

characterized by an extinction curve. Extinction curves are straightforward to measure using stars as these curves are simply the ratio of a reddened and unreddened star with the same surface physics (spectral type and metallicity). These curves combine the effects of dust absorption and scattering into a single measurement and show, among other features, the largest dust feature, the 2175 Å extinction bump (see Fig. 1a).

Our current view of dust is based, to a considerable extent, on measurements of UV dust extinction curves. Currently, there exist around 450 such extinction curves measured at spectroscopic resolution in the UV. Spectroscopic resolution is needed to produce high quality extinction curves that are not biased by spectral mismatches between the reddened and unreddened stars. These curves are mainly based on extensive International Ultraviolet Explorer (IUE) spectra taken in the Milky Way and the Magellanic Clouds. The IUE archive has been systematically studied and $\sim$400 extinction curves measured for the Milky Way (MW) (Valencic et al., 2004; Fitzpatrick & Massa, 2007). Almost all of these MW curves roughly can be described by a single parameter R(V) [= A(V)/E(B-V)] dependent relationship (Cardelli et al., 1989; Valencic et al., 2004), with a few outliers (Clayton et al., 2000; Valencic et al., 2003). The distribution of these extinction curves is shown in Fig. 1b and clearly illustrates that our knowledge of UV dust extinction curves is limited to just the $\sim$2 kpc around the Sun's location in the Milky Way.

The Magellanic Clouds provide the nearest galaxies in which we can easily measure dust extinction at different positions through a galaxy. Due to the relative faintness of stars

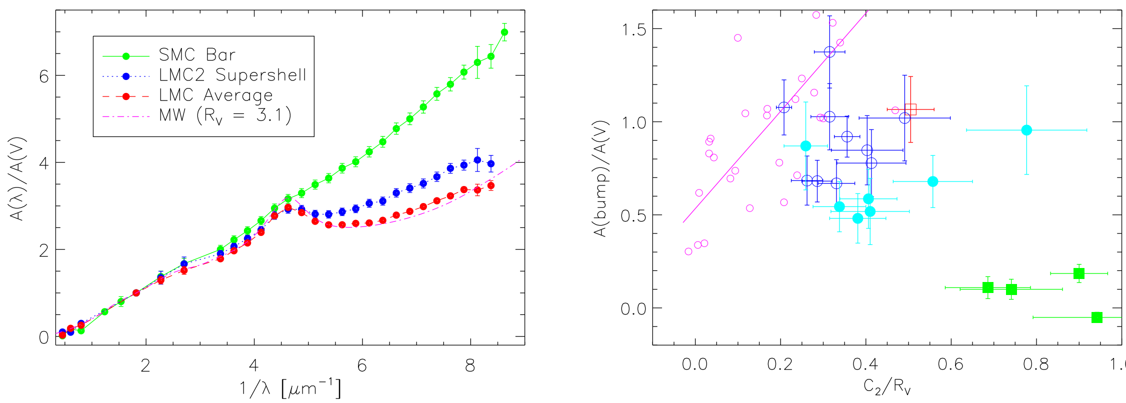

Figure 2: (a, left) The average MW, LMC and SMC extinction curves are shown. Figure from Gordon et al. (2003).
(b, right) The deviation of the LMC/SMC curves from the MW R(V) dependent relationship is shown along with the anti-correlation between the 2175 Å bump and UV slope ($C_3/R(F)$). The MW R(V) dependent relationship is sown as purple circles and line, LMC average sample are open blue circles, the LMC LMC2 supershell sample are closed cyan circles, the SMC AzV 456 sightline is an open red square and the SMC Bar sample are closed green squares. Figure from Gordon et al. (2003).

in these galaxies, the number of UV curves in both galaxies is much smaller than in the MW with 20 for the LMC (Misselt et al., 1999) and 9 for the SMC (Gordon & Clayton, 1998; Maíz Apellániz & Rubio, 2012). The majority of these curves deviate strongly from those seen in the MW. The most extreme variations are found in the SMC Bar where the curves have no 2175 Å bump and a very steep UV slope, yet in this same galaxy there are sightlines with strong 2175 Å bumps. Fig. 2a shows the average LMC and SMC curves with the average curve for the MW. The deviations of the LMC and SMC curves from the MW R(V) dependent relationship are shown in Fig. 2b demonstrating hints of an anti-correlation between the strength of the 2175 Å bump and the UV slope. In a the more distant M31, there is a detection of a possibly weaker than MW 2175 Å bump in M31 (Bianchi et al., 1996). These extragalactic extinction curves illustrates that the true range of properties of dust in the Universe is larger than our current understanding of MW dust and that observations across the faces of nearby galaxies are our current best measure of the true range of UV properties of dust.

The importance of measuring the true range of dust extinction curves is based on the fact that these curves provide the main basis for our understanding of dust grains, by providing constraints on their composition, size, and shape (Clayton et al., 2003; Weingartner & Draine, 2001; Zubko et al., 2004; Draine & Li, 2007). Our current models of dust grains are non-unique, because of the limited number of observational constraints. Progress on modeling dust grains will require a combination of laboratory studies on candidate materials, and, most importantly, improved observational constraints. In the observational area, one area

Table 1: Program Summary

Capability	Value
galaxies	M31, M33, LMC, SMC, NGC 6822
Photometric Survey	
band central wavelengths	1500, 1900, 2200, 2500, 3500, 4100
spatial resolution	FWHM ∼ 0.1”
sensitivity	S/N = 20, B5V star
survey area (5 galaxies)	70 sq. deg.
Spectroscopic Survey	
spectral resolution	1000
spectral coverage	1150–3000 Å
sensitivity	S/N = 50, B5V star
spectra needed	1200/galaxy

clearly promising to help better understand dust grains is the study of the correlation between observed dust properties and local environment. For example, the strength of the 2175 Å bump may be anti-correlated with the local massive star formation (Gordon & Clayton, 1998; Gordon et al., 2003).

Proposed Program

We are proposing a program to take a census of the dust properties in all the Local Group galaxies with significant dust. The set of measurements needed would be on the order of 1000 extinction curves in each galaxy. This would require UV spectra of on the order of 1200 massive stars (O5 - B5 spectral types) in each galaxy to provide measurements of 1000 sightlines and 200 comparison, unreddened stars (for direct comparison and constraints on stellar atmospheres). The sample size is set to provide a good sampling of the full range of dust extinction curves (50 sightlines) in broad spatial bins in each galaxy (20 spatial bins per galaxy). The Local Group galaxies to be targeted would be M31, M33, LMC, SMC, and NGC 6822. This sample of galaxies includes a massive spiral (M31), one dwarf spiral (M33), one dwarf disturbed spiral (LMC), and two irregular galaxies (SMC, and NGC 6822). These galaxies span a range of metallicities from somewhat above solar (M31) to around 1/5 solar (SMC). These galaxies have very low Milky Way foreground dust ensuring that the dominant dust signal is internal to target galaxy. These are well studied galaxies and the local environment region-by-region in each galaxies will be quantified using existing observations (e.g., ground-based H-alpha imaging for star formation, Spitzer/Herschel IR imaging for the average radiation field, Spitzer AGB star counts for dust production sites, and Hubble color magnitude diagrams for star formation history).

None of the Local Group galaxies targeted have 1000 massive, *reddened* stars identified in them. Thus, our proposed program would include a wide-field survey of the 5 galaxies using medium-band UV and blue-optical filters. The survey would include the full face of each galaxy to ensure the full extinction variation in each galaxy is probed. The filters would include 4 filters in the UV with central wavelengths of 1500, 1900, 2200, and 2500 Å to photometrically probe far-UV extinction (1500 Å) and the strength of the 2175 Å bump (other 3 filters). The combination of these 4 UV filters with blue-optical filters probing the Balmer jump (roughly Strömgren u and v) would provide high quality photometric spectral types and a rough measurement of the UV extinction curves (Massa et al., 1983). Additional bands at longer optical and near-infrared wavelength would improve the photometric spectral types and dust A(V) measurements, but are not strictly necessary. The spatial resolution needed is determined by crowding issues and is on the order of 0.1" (the PHAT HST M31 multi-cycle treasury is getting good results at this resolution). The sensitivity needed is set by need to reach B5V, the coolest, main sequence star that has enough far-UV flux to provide high quality extinction curves. Reaching to mid-B main sequence stars is required to probe less crowded environments as more massive O stars will generall be in more crowded regions and probe only the cores of star forming regions. We estimate a signal-to-noise of 20 in each band is needed to provide good photometric spectral types and dust A(V) measurements. The areas of each galaxy would be LMC (50 sq. deg.), SMC (15 sq. deg.), M31 (3 sq. deg.), M33 (1 sq. deg), and NGC 6822 (0.5 sq. deg.) for a total survey area of 70 sq. deg. The exposure time per point would be least in the largest galaxies as they are the closest.

Targets for the spectroscopic survey would be chosen from the best quality candidates from the photometric survey. The UV spectroscopy would need to have high enough signal-to-noise to provide the ability to obtain UV spectral types (Smith Neubig & Bruhweiler, 1997). Using ground-based telescopes to obtain classical blue-optical spectra is difficult given typical crowding of sources in these galaxies (especially M31, M33, & NGC 6822). A spectral resolution of 1000 provides high enough resolution to measure stellar features. The requested spectral range would be from 1150–3000 Å. This provides region around the 2175 Å bump as well as the far-UV region needed to determine UV spectral types. This region also include the Lyα line, providing high-quality measurements of the HI column density for these sightlines that would be useful for the analysis and interpretation of the dust extinction curves. Spectra in the blue-optical would be useful for tying the UV spectral types to the classical blue-optical spectral types, but is not required for this program. A multi-object capability would be ideal for this program given the relative compactness of our sources. The sensitivity is set by the need to obtain good signal-to-noise on a B5V star in our most distant galaxy (estimated at 50 to provide measurements of stellar features).

This program would generate datasets of photometry and spectroscopy that would be valuable in other areas of study. The photometric survey would produce A(V) and R(V) maps of all Local Group galaxies, with information on the full 3D structure of the ISM. Stellar populations studies would be possible with the same dataset, especially if coupled with similar data at longer wavelengths (e.g. PHAT-like). The large UV spectral library of hot, massive stars would provide for ample study of the early stages of stellar evolution over a range of metallicities and environments. These are just three of the many complimentary studies possible from the data obtained as part of this program.

RFI Details

Submitted in response to the Request for Information (RFI) for the "Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts" on 10 Aug 2012. Karl Gordon is the point of contact for this proposal. He is an Associate Astronomer at Space Telescope Science Institute. He is interested in participating in a workshop on this topic.

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The Baryon Census in a Multiphase Intergalactic Medium

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In this white paper, we summarize the current observations of the baryon census at low redshift (Shull, Smith, & Danforth 2012). We then suggest improvements in measuring the baryons in major components of the IGM and CGM with future UV and X-ray spectroscopic missions that could find and map the missing baryons, the fuel for the formation and chemical evolution of galaxies.

For low-redshift cosmology and galaxy formation rates, it is important to account for all the baryons synthesized in the Big Bang. Cosmologists have noted a baryon deficit in the low-redshift universe (Fukugita, Hogan, & Peebles 1998) relative to the predicted density synthesized in the Big Bang. Although this deficit could arise from an incomplete inventory, it could also challenge our understanding of the thermodynamics of structure formation and the response of the gas to accretion shocks and galactic outflows. Recent analysis (Komatsu et al. 2011) of the spectrum of acoustic peaks in the Cosmic Microwave Background (CMB) obtained by the *Wilkinson Microwave Anisotropy Probe* (WMAP) found that baryons comprise a fraction $\Omega_b = 0.0455 \pm 0.0028$ of the critical matter-energy density of the universe, $\rho_{\rm cr} = (9.205 \times 10^{-30}\ {\rm g\ cm^{-3}})h_{70}^2$, where h_{70} is the Hubble constant (H_0) in units of 70 km s^{-1} Mpc^{-1}. This corresponds to a comoving a hydrogen number density (at redshift $z = 0$) of only $n_H = (1.9 \times 10^{-7}\ {\rm cm^{-3}})h_{70}^2$.

An inefficient distribution of collapsed baryons vs. distributed matter is a prediction of nearly all cosmological simulations (see Figure 1a) of large-scale structure formation (Cen & Ostriker 1999, 2006; Davé et al. 1999, 2001; Smith et al. 2011; Tepper-Garcia et al. 2011). These N-body hydrodynamical simulations suggest that 10–20% of the baryons reside in collapsed objects and dense filaments, with the remaining 80% distributed over a wide range of phases in baryon overdensity ($\Delta_b = \rho_b/\overline{\rho}_b$) and temperature ($T$). In fact, a shock-heated WHIM at $z < 1$ is a natural consequence of gravitational instability in a dark-matter dominated universe. This hot gas is augmented by galactic-wind shocks and virialization in galaxy halos. Together, these processes affect the rate of accretion onto galaxies (cold-mode or hot-mode) and control the process of galaxy and star formation.

Unfortunately, the observed baryon inventories in the low redshift universe are uncertain. Theoretical estimates of the physical state of the gas are complicated by the formation

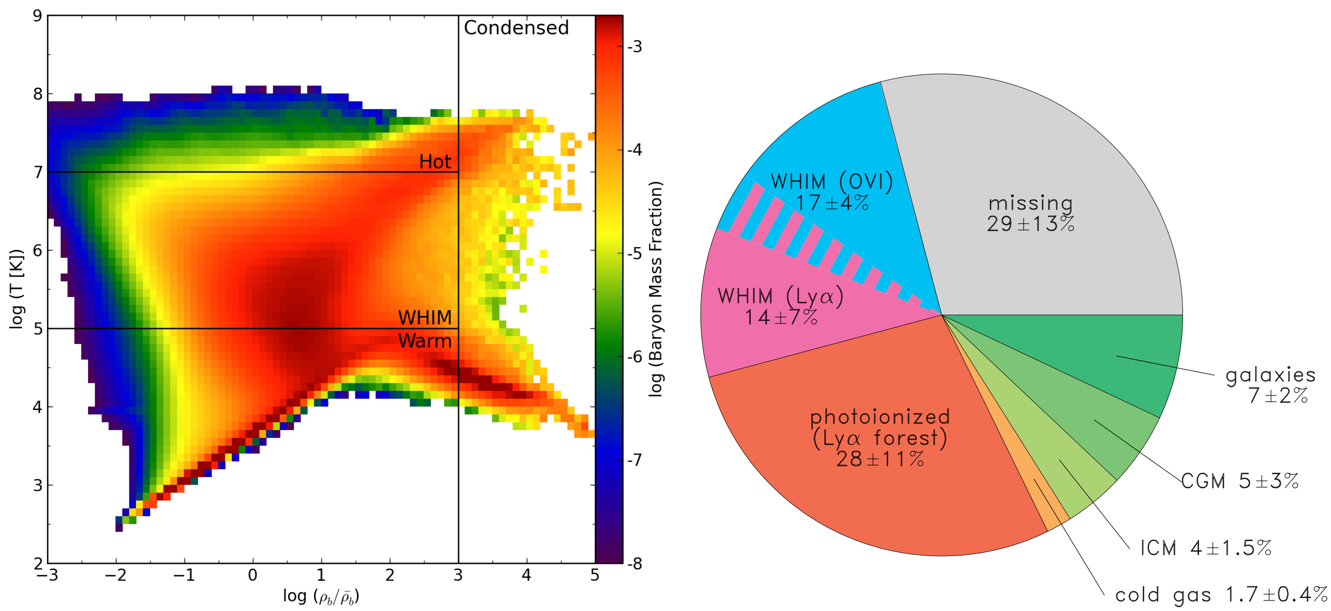

Fig. 1.— Figures from recent study by Shull, Smith, & Danforth (2012). (Left) Simulated distribution of IGM in temperature T and baryon overdensity $\Delta_b = \rho_b/\overline{\rho}_b$, color-coded by baryon mass fraction. Distribution shows the thermal phases, commonly labeled as warm (diffuse photoionized gas), WHIM, and condensed. (Right) Compilation of current observational measurements of the low-redshift baryon census. Slices of the pie-chart show baryons in collapsed form, in the circumgalactic medium (CGM) and intercluster medium (ICM), and in cold gas (H I and He I). The primary baryon reservoirs include diffuse photoionized Lyα forest and WHIM traced by O VI and broad Lyα absorbers. Collapsed phases (galaxies, CGM, ICM, cold neutral gas) total $18 \pm 4\%$, and $29 \pm 13\%$ of the baryons remain unaccounted for. An additional 15% may reside in X-ray absorbing gas at $T \geq 10^{6.3}$ K. Even more baryons may be found in weaker lines of low-column density O VI and Lyα absorbers. Deeper spectroscopic UV and X-ray surveys are required to find and characterize this IGM and CGM, gas that provides fuel for new stars and galaxy formation.

of galaxies and large-scale structure and the feedback from star formation in the form of ionizing radiation, metals, and outflows. Galaxy surveys have found ∼10% of these baryons in collapsed objects such as galaxies, groups, and clusters (Salucci & Persic 1999; Fukugita & Peebles 2004). Over the last 15 years, substantial reservoirs of gas have also been found in the intergalactic medium (IGM), in the halos of galaxies, and in the circumgalactic medium (CGM), including metal-enriched gas blown out of galaxies (Tumlinson et al. 2011; Prochaska et al. 2011). Of the remaining 80-90% of cosmological baryons, approximately half can be accounted for in the low-z IGM (Bregman 2007; Danforth & Shull 2008) including the warm-hot IGM (or WHIM). Ultraviolet spectroscopic surveys of Lyα and O VI have identified substantial numbers of absorbers (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008), but claimed detections of hotter in X-ray absorption by O VII (Nicastro et al. 2005a,b) remain controversial (Kaastra et al. 2006; Yao et al. 2012). Unfortunately, X-ray spectra still have not confirmed the potential large reservoir of baryons at $T > 10^6$ K.

Observations (Figure 1b) of the "Lyman-α forest" of absorption lines suggest that it contains ∼30% of the low-z baryons (Penton et al. 2000, 2004; Lehner et al. 2007; Danforth & Shull 2008). Another 30–40% is predicted by simulations to reside in shock-heated gas at 10^5 K to 10^7 K (WHIM). These two components account for 60–70% of the cosmological baryons. However, owing to its low density, the WHIM is difficult to detect in emission (Soltan 2006). More promising are absorption-line studies that use the high ionization states of abundant heavy elements with resonance lines in the far-ultraviolet (C IV, N V, O VI), extreme ultraviolet (O IV, O V, Ne VIII), and soft X-ray (O VII, O VIII, N VI, Ne IX). Gas in the temperature range $5 < \log T < 6$ can also be detected in broad Lyα absorption (Richter et al. 2004; Danforth et al. 2010) arising from trace amounts of neutral hydrogen with neutral fractions $-6.6 < \log f_{\rm HI} < -4.8$. By far, the most effective surveys of the low-z WHIM were obtained from the O VI lines at 1031.926 Å and 1037.617 Å (Danforth & Shull 2008; Tripp et al. 2008; Thom & Chen 2008), which probe the temperature range $10^{5.3-5.7}$ K in collisionally ionized gas. Tilton et al. (2012) measured the column densities of 111 O VI absorbers and estimated that $17 \pm 4\%$ of the baryons reside in this phase, assuming new correction factors for the metallicity and O VI ionization fraction (Shull et al. 2012). A few detections of Ne VIII have also been reported (Savage et al. 2005, 2011; Narayanan et al. 2009, 2011; Meiring et al. 2012) probing somewhat hotter gas ($\log T \approx 5.7 \pm 0.2$).

To detect even hotter portions of the WHIM at $\log T > 6$ requires X-ray searches for trace metal absorption lines from highly ionized C, O, or Ne. Their weak X-ray absorption lines are difficult to detect with the current throughput and spectral resolution of spectrographs on *Chandra* and *XMM/Newton* (Yao et al. 2012). Possible X-ray detections of hotter gas at $(1-3) \times 10^6$ K have been claimed, using absorption lines of helium-like O VII λ21.602 (Nicastro et al. 2005a,b, 2008; Buote et al. 2009; Fang et al. 2010; Zappacosta et al. 2010) and hydrogenic O VIII λ18.969 (Fang et al. 2002, 2007). Most of these *Chandra* detections remain controversial and unconfirmed by the *XMM-Newton* satellite (Kaastra et al. 2006; Williams et al. 2006; Rasmussen et al. 2007). For example, recent analyses of spectroscopic data on Mrk 421 fail to detect any WHIM gas at the claimed redshifts ($z = 0.01$ and 0.027), either in broad Lyα absorption (Danforth et al. 2011) from high-S/N data from the Cosmic Origins Spectrograph (COS) on the *Hubble Space Telescope* (*HST*) or in O VII (Yao et al. 2012) in *Chandra* data.

Figure 1b shows a pie chart of the current observable distribution of low-redshift baryons in various forms, from collapsed structures to various phases of the IGM, CGM, and WHIM. The slices show contributions, $\Omega_b^{(i)}/\Omega_b^{(\mathrm{tot})}$, to the total baryon content from components (i). Measurements of Lyα, O VI, and broad Lyα absorbers, together with more careful corrections for metallicity and ionization fraction, can now account for $\sim 60\%$ of the baryons in the IGM. An additional 5% may reside in circumgalactic gas, 7% in galaxies, and 4% clusters. *This still leaves a substantial fraction,* $29 \pm 13\%$*, unaccounted for.*

What observations and theoretical work are needed to make progress on the baryon census, both in sensitivity and in accuracy? First, we need more precise UV absorption-line surveys to measure O VI and Lyα absorbers to lower column densities. The numbers of absorbers in current surveys become increasingly uncertain at column densities $N_{\mathrm{HI}} < 10^{13.0}\mathrm{cm}^{-2}$ and $N_{\mathrm{OVI}} < 10^{13.5}\mathrm{cm}^{-2}$. Finding and mapping this IGM/CGM fuel supply will require new generation of spectrographs, optics, and high-precision detectors on a larger telescope ($D \geq 4^{\mathrm{m}}$ aperture. These weak-absorber surveys will require sensitivity to 2 mÅ equivalent widths, which is achievable at S/N = 50 toward many bright AGN background targets. We also need to obtain better detections and statistics for broad Lyα absorbers (BLAs) and the Ne VIII doublet (770.4, 780.3 Å). The Ne VIII lines are potentially more reliable probes of hot, collisionally ionized gas than O VI, since Ne VIII requires 207 eV to produce and is likely to be less contaminated by photoionization. Redshifts $z > 0.47$ are needed to shift these EUV lines into the *HST*/COS band, but new far-UV missions with sensitivity down to 1000 Å would open up many more AGN targets at $z > 0.30$. The BLAs also have considerable promise for WHIM probes, as they do not require corrections for metallicity. They do require determining the neutral fraction, f_{HI}, through careful modeling of the gas temperature and ionization conditions.

It would also be helpful to verify the claimed X-ray detections of O VII in the WHIM, most of which are not confirmed. These new observations will allow us to explore the mixture of collisional ionization and photoionization in the WHIM, a project that requires understanding the implications of different feedback mechanisms for injecting mass, thermal energy, and metals into the CGM. How these metals mix and radiate likely determines the thermodynamics of the surrounding IGM.

The most critical observations for the WHIM census will require a next generation of X-ray spectrographs to measure the weak absorption lines of O VII λ21.602, O VIII λ18.969, and other He-like and H-like lines of abundant metals (C V, C VI, N VI, N VII). As discussed by Yao et al. (2012), this requires high-throughput spectrographs ($E \approx 0.3 - 1.0$ keV) with energy resolution $E/\Delta E > 4000$ sufficient to resolve O VII absorbers with mÅ equivalent width. For weak lines, the predicted O VII equivalent widths are $W_\lambda = (2.88 \text{ mÅ})(N_{\rm OVII}/10^{15} \text{ cm}^{-2})$.

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Quasar Absorption Lines in the Far Ultraviolet: An Untapped Gold Mine for Galaxy Evolution Studies

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ABSTRACT

Most of the baryons are exceedingly difficulty to observe, at all epochs. Theoretically, we expect that the majority of the baryonic matter is located in low-density, highly ionized gaseous envelopes of galaxies – the "circumgalactic medium" – and in the highly ionized intergalactic medium. Interactions with the CGM and IGM are thought to play crucial roles in galaxy evolution through accretion, which provides the necessary fuel to sustain on-going star formation, and through feedback-driven outflows and dynamical gas-stripping processes, which truncate and regulate star formation as required in various contexts (e.g., low-mass vs. high-mass galaxies; cluster vs. field). Due to the low density and highly ionized condition of these gases, quasar absorption lines in the rest-frame ultraviolet and X-ray regimes provide the most efficient observational probes of the CGM and IGM, but ultraviolet spectrographs offer vastly higher spectral resolution and sensitivity than X-ray instruments, and there are many more suitable targets in the UV, which enables carefully designed studies of samples of particular classes of objects. This white paper emphasizes the potential of QSO absorption lines in the rest-frame far/extreme UV at $500 \lesssim \lambda_{\rm rest} \lesssim 2000$ Å. In this wavelength range, species such as Ne VIII, Na IX, and Mg X can be detected, providing diagnostics of gas with temperatures $\gg 10^6$ K, as well as banks of adjacent ions such as O I, O II, O III, O IV, O V, and O VI (and similarly N I – N V; S II – S VI; Ne II – Ne VIII, etc.), which constrain physical conditions with unprecedented precision. A UV spectrograph with good sensitivity down to observed wavelengths of 1000 Å can detect these new species in absorption systems with redshift $z_{\rm abs} \gtrsim 0.3$, and at these redshifts, the detailed relationships between the absorbers and nearby galaxies and large-scale environment can be studied from the ground. By observing QSOs at $z = 1.0 - 1.5$, *HST* has started to exploit extreme-UV QSO absorption lines, but *HST* can only reach a small number of these targets. A future, more sensitive UV spectrograph could open up this new discovery space.

1. QSO Absorption Lines at Wavelengths < 912 Å

High-resolution ultraviolet spectroscopy provides a unique ability to study low-density gas/plasma in galaxy disks, halos, and the intergalactic medium (IGM), i.e., all harbors of present-epoch baryons. Since stars account for only a small fraction of the baryon inventory and most of the ordinary matter is in very low-density gases (Fukugita et al. 1998, ApJ, 503, 518), UV spectroscopy is a crucial technique for the study of galaxy ecosystems and the cycles of inflowing and outflowing matter and energy that regulate galaxy formation. As anticipated by Verner et al. (1994, ApJ, 430, 186), the deployment of the *Cosmic Origins Spectrograph* (COS, Green et al. 2012, ApJ, 744, 60) on the *Hubble Space Telescope* has demonstrated a particularly powerful new window for UV spectroscopy: the study of QSO absorption lines in the "extreme" ultraviolet (EUV) at $\lambda < 912$ Å. Normally, we assume that EUV absorption lines cannot be observed because the Galactic ISM prevents observations of transitions at these wavelengths in the Milky Way. However, if gas in a quasar absorption system has a sufficiently high redshift, these lines are redshifted into the *HST* bandpass; for example, the Ne VIII doublet at 770.4,780.3 Å can be studied in QSO absorbers with redshift $z_{\rm abs} \geq 0.3$ with a spectrograph sensitive down to 1000 Å. Unfortunately, in very high-redshift QSO absorbers that can be observed from the ground, these EUV lines are ruined by blending with the thick Lyα forest. However, as illustrated in Figure 1, QSOs at $z \approx 1 - 1.5$ are in a "sweet spot" where the EUV lines can be detected but the line density is low enough so that blending is not severe. These COS data demonstrate the potential of EUV lines, but unfortunately, HST+COS can only access a small number of these targets in reasonable exposure times. Moreover, while the COS spectra have signal-to-noise $\approx 30 - 50$ per resel, higher S/N ($\gtrsim 100$) would greatly improve this technique because the key lines (e.g., Ne VIII) can be quite weak (see, e.g. Meiring et al. 2012, arXiv1201.0939).

Figure 2 demonstrates the following unique diagnostics provided by EUV absorption spectroscopy: First, EUV absorption lines include species such as Ne VIII, Mg X, and Si XII, and these species are detectable in plasmas at $T > 10^6$ K. Thus, in the EUV, *HST* can compete with X-ray telescopes, but *HST* has much better spectral resolution, better sensitivity, and a substantially larger pool of sufficiently bright targets, which enables more optimal target selection. The Astro2010 decadal survey identified the *International X-ray Observatory* as a top priority for the next 20 years, and one of the prime science drivers of IXO is the study of missing baryons and hot gas in low-density gaseous halos and the IGM using absorption spectroscopy. By using species such as Ne VIII and Mg X, we can pursue this IXO science goal immediately. We have already successfully detected Ne VIII, Mg X, and other highly ionized hot-gas tracers (see below). Second, the EUV includes transitions of suites of adjacent ions such as O I, O II, O III, O IV, O V, and O VI or S II, S III, S IV, and S V (similar sets are available for C, N, etc). These adjacent ions span a wide range of

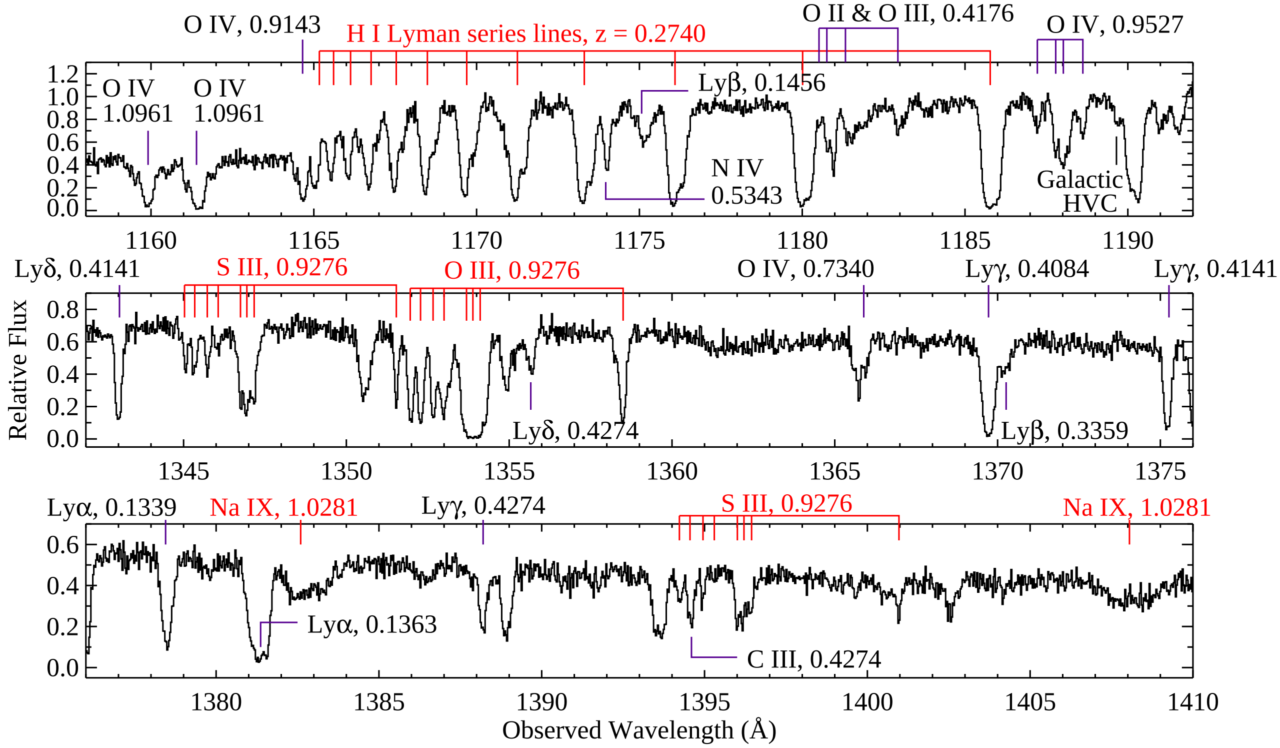

Fig. 1.— Examples of the COS spectra obtained from our *Hubble Space Telescope* program from the sight lines to PG1630+377 ($z_{\rm QSO} = 1.476$, top panel) and PG1206+459 ($z_{\rm QSO} = 1.163$ middle and lower panels). Various lines of metals and H I are labeled with their redshifts. **Most of the lines in this figure have rest-frame wavelengths < 912 Å; the shortest-wavelength transitions shown here are the Na IX doublet with $\lambda_{\rm rest} = 681.7, 694.3$ Å and the O IV lines at $\lambda_{\rm rest} = 553.3, 554.1$ Å.** Lines and systems of particular interest are indicated in red. The high S/N of these data and access to lines down to the H I Lyman limit (and beyond) provide very precise constraints on the H I column densities, the ionization state of the gas, the metallicity, gas kinematics, and insights on the multiphase physics that governs circumgalactic and intergalactic gases. Note that these are only small portions of the spectrum for each quasar and are representative of the full sample.

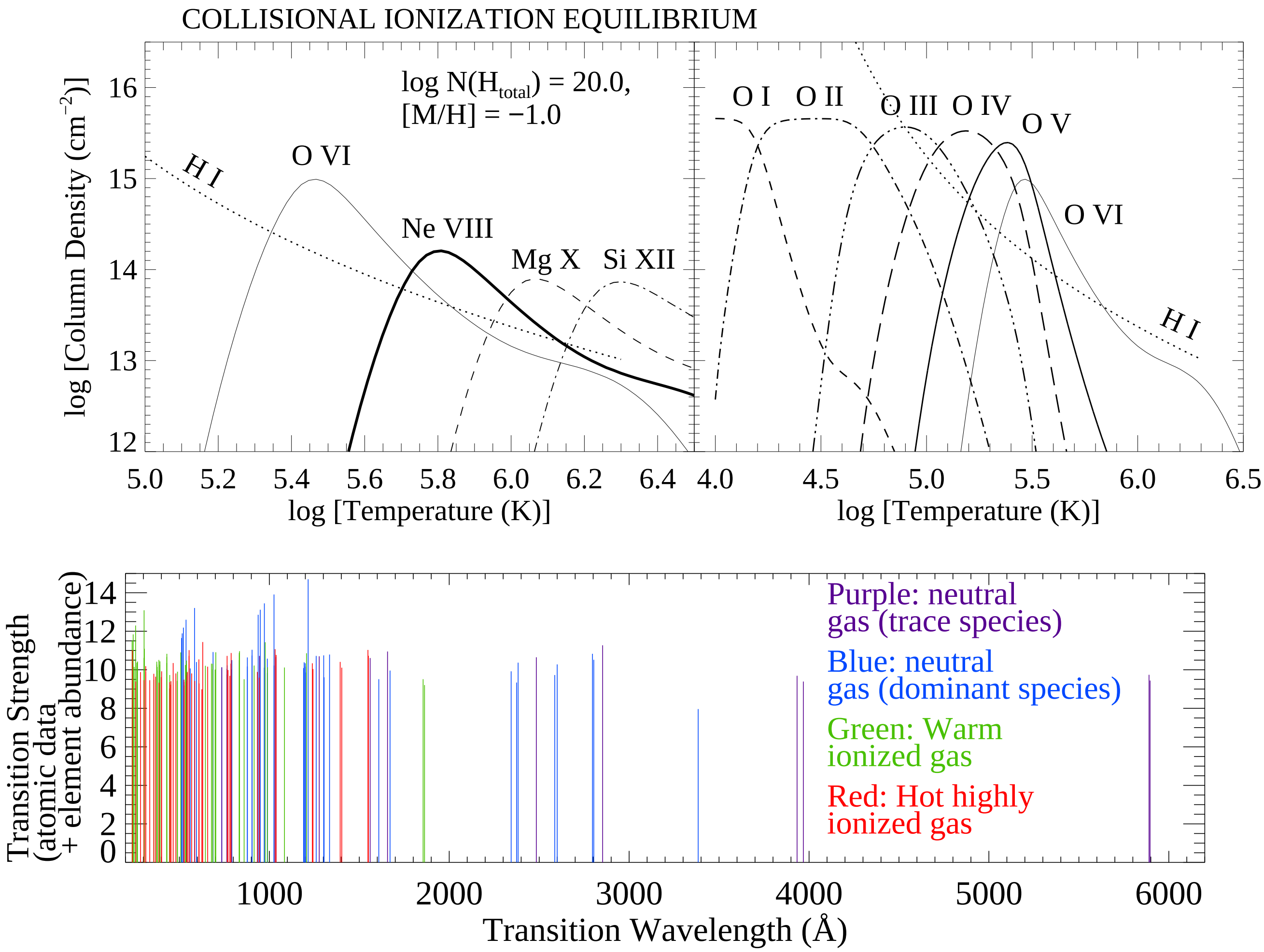

Fig. 2.— *Upper panels:* Column densities of various metals in collisional ionization equilibrium, as a function of temperature, for an absorber with $N(\mathrm{H_{total}}) = 10^{20}$ cm^{-2} and $Z = 0.1Z_{\odot}$. *Lower panel:* Strength of resonance lines vs. the rest-frame wavelength of the transition from Verner et al. (1994, A&AS, 108, 287) based on the element abundance and atomic data (taller lines indicate intrinsically stronger transitions). Colors indicate tracers of difference gas phases (see legend). In addition to providing access to a larger number of sight lines, a future UV spectroscopic facility with greater sensitivity could more effectively exploit the rich diagnostics available at $\lambda < 1000$ Å by detecting weaker lines with higher signal-to-noise spectra.

temperatures/ionization conditions (see Fig. 2), and limits on or detections of these species can constrain the physics and metallicity of QSO absorbers with unprecedented precision [note that currently, we typically only have access to scattered ionization stages such as O VI, C III, and Si III in low-N(H I) absorbers]. As shown in the lower panel of Fig. 2, the EUV is the richest region of the spectrum for QSO absorption spectroscopy. Third, the redshifts of the absorbers are sufficient to bring many H I Lyman series lines into the *HST* band (see examples in Figure 1). This enables accurate H I column-density measurements because the higher Lyman series lines are less likely to be saturated. Observations of lower-redshift absorbers often detect only a few Lyman lines or even only Lyα, and often these lines are badly saturated so N(H I) is highly uncertain. Uncertain N(H I) measurements lead to uncertain metallicity measurements. With good constraints on metallicity and physical conditions, key properties such as mass and mass flow rates can be estimated.

2. Proof of Concept: First Results from *HST*

Galactic Winds Driven by Star Formation and AGN. The role of galactic outflows and "feedback" is one of the most pressing issues of current galaxy evolution studies. Some observations of objects such as Lyman-break galaxies, ULIRGs, and post-starburst galaxies have revealed dramatic outflows (e.g., Rupke et al. 2005, ApJS, 160, 87; Tremonti et al. 2007, ApJ, 663, L77; Steidel et al. 2010, ApJ, 717, 289). However, since these studies usually use the ULIRG or the post-starburst galaxy itself as the continuum source, they suffer from an ambiguity regarding the spatial extent, and hence the mass, of the outflow. These investigations also have a limited suite of diagnostics, e.g., Mg II or Na I and nothing else. By using absorption lines imprinted on background QSOs, these limitations can be overcome, and the EUV lines turn out to be particularly interesting. Multiple examples of different types of outflows are present in the sample COS data shown in Figure 1. For example, toward PG1206+459 we have clearly detected, at high significance, a doublet of Na IX at $z_{\rm abs}$ = 1.0281 (see the lowest panel in Fig. 1). Na IX has never been detected before, but this absorber is also detected in Ne VIII, Mg X, Ar VII, Ar VIII, and O V.

A possibly even more interesting outflow is detected at $z_{\rm abs}$ = 0.9276 in the PG1206+459 spectrum (Tripp et al. 2011, Science, 334, 952). From Fig. 1 we see that there is a dramatic cluster of absorption lines at this redshift detected in species such as S III and O III (middle and lower panels). This system is notable for the following reasons (see Tripp et al. for full details): First, we detect the adjacent suites of ions, including O III, O IV, O V, and O VI; N III, N IV, and N V; and S III, S IV, and S V. Second, we detect Ne VIII at very high significance. Third, the Ne VIII and N V velocity centroids are strongly correlated with the centroids of low ions such as Mg II, Si II, and C II (see Fig.3 in Tripp et al.). Fourth, while this absorption cluster is clearly a Lyman-limit absorber with many higher Lyman-series lines, the Lyman limit (LL) is not black and excellent N(H I) measurements can be obtained.

Finally, there is a post-starburst galaxy with an AGN at an impact parameter of 68 kpc from the sight line. These results have interesting implications: (1) The components in the cluster extend from -400 to $+1100$ km s^{-1}; with these velocities, some components must be exceeding the escape velocity of the galaxy. (2) Using the adjacent ions (e.g., SIII/SIV/SV) we can pin down the ionization state of each component and estimate their total column densities. Combined with the large impact parameter (70 kpc) to the galaxy, this implies that each component carries $\approx 10^8$ M$_\odot$ of mass in cool, photoionized gas, assuming a standard thin-shell model (e.g., Tremonti et al. 2007). Other geometries would give different masses, but an important mass component is implicated in any case. (3) However, the Ne VIII and N V must arise in hot gas that is correlated with the cool gas – Ne VIII/N V cannot originate in the cool photoionized gas. Moreover, this hot gas contains $10\times$ to $150\times$ more mass than the cool phase. In addition, the remarkable correspondence of the Ne VIII with lower ions suggests that the outflowing material is also interacting with a hotter (unseen) phase. How do species like Mg II and Si II survive at these outflow velocities embedded in such hot gas?

Cold Accretion of Pristine (Low-Metallicity) Gas. These spectra also reveal the opposite process: absorbers that are most naturally explained as cold, *inflowing* material, an equally important topic that is even more poorly constrained by observations. The partial Lyman limit absorber that produces the Lyman series lines shown in the top panel of Figure 1 is an example of apparently infalling, very metal poor gas. We have analyzed the metals affiliated with this partial Lyman limit system (Ribaudo et al. 2011, ApJ, 743, 207), and we find that the logarithmic metallicity is only [Mg/H] $= -1.71 \pm 0.06$. Moreover, we have spectroscopically identified and studied a nearby galaxy at the redshift of the Lyman limit absorber at an impact parameter of 37 kpc. Interestingly, that galaxy has a metallicity that is almost two orders of magnitude higher, $[\mathrm{O/H}]_{\mathrm{galaxy}} - 0.20 \pm 0.15$. This absorber may represent nearly primordial material that is accreting onto the galaxy via cold-mode accretion (Kereš et al. 2005), but other explanations remain viable. Subsequently, we studied all LL absorbers ($16.0 < \log N(\mathrm{H\ I}) < 19.$) in our data combined with measurements from the *HST* archive and literature (Lehner et al. 2012, in prep.), and we find that 50% of LL have very low-metallicity ($Z \leq 0.03 Z_\odot$). Our survey has tripled the sample of LL absorbers with good metallicity measurements at $z < 1$, but the sample is still small (28 systems total).

Requirements for a Future UV Telescope. Technical concepts are deferred to the second RFI, but the key technical requirements for this science can be briefly summarized. While *HST* has begun to observe QSO absorption lines at $\lambda_{\mathrm{rest}} < 912$ Å, the number of $z_{\mathrm{QSO}} = 1 - 2$ QSOs bright enough for *HST* is extremely small. To exploit this discovery space, a future UV spectrograph must have substantially better sensitivity than *HST*+COS, good spectral resolution (comparable to STIS and COS), and wavelength coverage down to at least 1150 Å and preferrably down to ≈ 1000 Å.

SEEKING BEHIND THE ANTHROPIC PRINCIPLE

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The Universe must have the properties which allow life to develop within it at some stage.

Our Universe is but one of many possible worlds. For humans to exist, a remarkable fine tuning of the laws of physics and the fundamental constants is required. Cosmological models possessing different initial conditions but with the same laws do not necessarily evolve to produce a Universe like ours, 13.7 billion years after the Big Bang. What does produce universes like ours?, which subset of the possible universes allows the emergence and eventual evolution of life?

Astrophysics research has sought actively the answer to these questions though the quest is biased; the *observable* Universe is just the (small) fraction of the actual Universe causally connected to our present.

During the last two decades, some amazing results from this exploration have come up such as the discovery of the Cosmic Web and the anisotropy of the cosmic background or the realization that planetary systems are widespread. Major attempts to reach information from redshifts above six have been implemented yet, the time span from redshift two to present covers about 80% of the life of the Universe. It is in the time frame that life emerges because metals are widespread, the star formation pace has slowed down favoring diffuse star formation where planetary systems can actually survive and the interaction between a rich ultraviolet field and matter accelerates the organic chemistry and creates the environment for complex molecules to survive in planets protected against the harsh space environment.

The anthropic principle is about the emergence of life, of complex and intelligent life. For that, nucleosynthesis needs to have proceeded to enrich significantly the interstellar medium and guarantee that carbon, nitrogen, oxygen and phosphor are widespread in the Universe. Studies of the metal abundance variation up to redshift 5 are showing that the metallicity increases steadily with the age of the Universe. However there are numerous evidences of a large scatter in the metallic properties of matter for any given z; non metal-enriched clouds have been detected and chemically processed material has been found in the voids of the Comic Web. Meanwhile, the star formation rate seems, to be decaying from z=1. Important clues on the metal enrichment spreading on the Universe hang on inter-galactic transport processes such as galactic winds or the effect of galactic interaction in halos that are poorly studied because of the lack of high sensitivity imaging capabilities to detect the warm/hot plasma emission from galactic halos. Current information comes from absorption spectroscopy that it is a rather inefficient technique to map the large scales involved and requires the presence of strong background sources. Moreover, most of the emission is expected to come from filaments and chimneys that will require a high sensitivity imaging capability with resolutions at least ten times better than those provided by the GALEX mission.

Galactic halos are made of collision less plasmas, very sensitive to fields and waves. Thus, they can be used as a good diagnostic tool for variations in the galactic gravitational field, or in more subtle fields as those that might be associated with dark energy.

Metallicity is relevant for life generation not only at the DNA level but also at much earlier phases. Silicates and carbonates are the key building blocks of dust grains in protostellar disks; dust grains get charged by the absorption of UV radiation and their charging profiles depends on the hardness of the spectrum. Solar precursors produce harder radiation fields than massive stars. Extreme UV radiation is a major actor in protostellar disk evolution. It drives to the photoevaporation of the gas compound from the disk releasing the rocky planetesimals for planetary building up. Unfortunately, little is known about the EUV radiation from solar-system precursors. The measurements carried out in X-ray or softer UV bands point out that the EUV flux varied significantly during the pre-main sequence evolution. Protostellar disk were shielded from hard radiation only in the early phases but then, a source of disk ionization must be searched for to guarantee the accretion process.

After 1 million years, protostellar disks are transformed into young planetary disks and the EUV radiation from a very active young Sun heavily irradiates them. The very active stellar winds are expected to interact with the left over particles and produce diffuse Helium and Hydrogen emission that pervades the whole young systems during planets early evolution and planetary magnetosphere formation. Around the Sun, within a modest radius of 140 pc, there thousands of young solar-like stars in all evolutionary stages. A modest spectral resolution instrument to measure the EUV spectra of these sources and compare it with that of our Sun will provide a unique perspective magnetospheres and coronal evolution, as well as on its impact in planetary formation and evolution.

But the study of the last ten billion years of the life of the Universe is also interesting for fundamental reasons. It is in this time lapse that the accelerated expansion of the Universe has been discovered. Moreover, marginal evidence of small variations of the fine structure constant have been reported for redshifts 1.5-2 . The fine structure constant, $\alpha=e^2/\hbar c$, is the parameter that governs the strength of electromagnetism; it couples the electromagnetic field to all charged particles in nature. Unfortunately, measurements are ground-based and subjected to the uncertainties of the atmospheric refraction index that it is a major source of error. The accurate *many multiplet* method makes use of resonance transitions from Fe II and Mg II, radiated in the ultraviolet in the rest frame and redshifted into the optical range by the cosmological expansion. Measurements from space would be much more accurate provided that stable high resolution spectroscopy and a high collecting surface to reach z=2 is provided. Also, space opens up the possibility to use stronger multiplets like the Lyman series of Hydrogen.

Behind these measurements resides the basis of quantum physics and the understanding of vacuum fluctuations and energy. Vacuum energy was first hypothesized to model the Lamb shift detected in the Hydrogen atom. Would it be possible to measure the Lamb shift in remote sources, up to redshift 2?. This is a most challenging measurement because not only a very efficient large collecting surface is required but also a complex experimental set-up, difficult to operate in space . Maybe, a Moon-based lab could be set-up to measure the Lamb shift in astronomical sources up to z=2.

To conclude, along the path that drives from the Big Bang to intelligent life there are cross-roads, critical steps that made feasible our Universe, some of them are the accelerated expansion, the chemical processing of matter, the metal mixing in the Universe, the interplay between UV radiation and matter to finally produce planets and life. Facilities to detect the UV radiation from the observable Universe up to z=2 are required. The largest discovery potentials are in:

1. high sensitivity, high resolution imaging from 1000 to 4000 Å to map the intracluster medium and galactic halos, chimneys and winds.
2. high sensitivity, high resolution spectroscopy from from 1000 to 4000 Å to measure the evolution of the fine structure constant till z=2
3. low resolution (500-1000) EUV spectroscopy to reach the nearest star forming laboratories at 140 pc to follow the pre-main sequence evolution of magnetospheres and winds in solar-like stars.

Ana I Gómez de Castro – 10th August 2012

I am willing to attend and participate in a workshop if invited

The escape fraction of ionizing photons from dwarf galaxies

Corresponding Author: **Scarlata** Claudia, assistant professor, Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis (MN). Email: scarlata@astro.umn.edu, phone: +1-612-626-1811. The author will be willing to present the science case at a workshop.

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Executive summary: Measuring the escape fraction of ionizing photons from galaxies is a crucial step in understanding the reionization of the Universe, a central question in the COR program. We highlight how this goal can be achieved with deep imaging down to 2000A (reaching NUV~32, i.e., about 10 times deeper than the currently deepest HST observations), over a large field of view (a few times Hubble's WFC3). We also briefly discuss the importance of deep spectroscopy in the NUV, to understand the mechanisms that allow the escape of ionizing radiation and to constrain the line-of-sight specific IGM absorption.

Introduction

The "dark ages" in the history of the Universe ended with a drastic change in the ionization state of the intergalactic medium (IGM), which went from completely neutral to completely ionized. The timing of this transition -hereafter reionization- is constrained observationally through the Gunn-Peterson absorption in the spectra of z>6 QSOs and through the polarization of the Cosmic Microwave Background. Results from these studies favor an inhomogeneous and extended reionization process, over the redshift range 6 – 15 (e.g., Songaila 2004, Fan, Carilli & Keating 2006, Jarosik et al. 2011).

Many aspects of the reionization process remain uncertain, with the most crucial one being the nature of the sources producing the bulk of the ionizing radiation (e.g., with energy below one Ry). It is generally accepted that the IGM is kept ionized by the combined UV radiation from AGN and star-forming galaxies, and at low-redshift there are easily enough sources (Cowie et al. 2009). At earlier stages, however, the large uncertainties in the evolution of the QSO/AGN luminosity function (LF), together with the weak constraints on the evolution of the faint end of the galaxy LF result in a much less clear picture (Fontanot et al. 2012). More important still, in order to estimate the ionizing contribution from any population of sources, the fraction of the intrinsic ionizing luminosity that is able to escape from them and reach the IGM – the escape fraction of Lyman continuum (LyC) photons, f^{LyC}_{esc} – must be known. Thus, f^{LyC}_{esc} currently represents the Holy Grail in the quest for the understanding of one of the most important changes in our Universe.

Constraining f^{LyC}_{esc}: what do we need

Ideally, we would like to measure the escape fraction from sources as close as possible to the reionization epoch. As Figure 1 shows, this is close to impossible. Albeit with a large line-of-

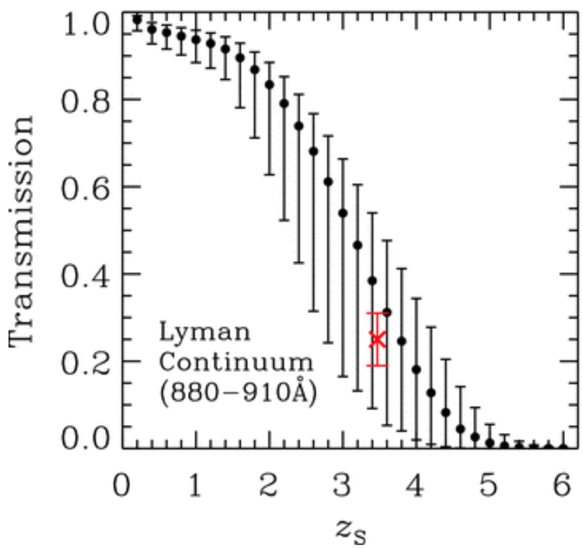

Figure 1: Average IGM transmission as a function of the source redshift, computed in the rest frame 880-910A (from Inoue & Iwata 2006).

sight variation, the average IGM transmission of ionizing photons decreases quickly with redshift from about 95% at z~1 to substantially zero at $z\geq5$. For this reason, the measurement has to be performed at lower redshifts, where the average IGM transmission allows it. Moreover, a serious problem in measuring f^{LyC}_{esc} is the contamination due to chance alignment between the high redshift target and a faint foreground galaxy (e.g., Vanzella et al. 2010). This can be alleviated with precise spatial information from space together with deep NIR spectroscopy (with 10-m class telescopes or, later, JWST) to rule out interlopers, and by performing the study in low(er) redshift galaxies. Because of the UV atmospheric cut-off, the lowest redshift at which the measurement can be performed from the ground is z>2.7, where the average IGM transmission is about 50%, just below the Lyman limit (Figure 1).

Pushing the search for escaping Lyman continuum to redshifts lower than 2.7 requires space based NUV observations, but provides four crucial advantages (apart from the obvious one of appearing brighter for a given UV luminosity):

1. already by z~1.5, the average IGM transmission is 90%, and

2. the scatter in the IGM transparency from different lines of sight is substantially smaller than at higher redshifts, reducing the uncertainty on the measured f^{LyC}_{esc} (see below).

3. The Hα line (required to constrain the *absolute* escape fraction[a]) is accessible up to z~2.5 with near-IR spectroscopy from the ground or wide-field space telescopes (Euclid to z~2 or WFIRST potentially to z~2.5).

4. The rate of contamination by lower redshift galaxies is substantially reduced.

Constraining f^{LyC}_{esc}: where do we stand

Measurements of galaxies at $z<3.5$ show the average f^{LyC}_{esc} to be very low or undetected at all redshifts. Despite the hundreds of hours invested on both HST and 8–10m class telescopes, the hunt for leaking ionizing photons has yielded an extremely small number of detections (Grimes et al. 2007, Iwata et al. 2009; Siana et al. 2010; Bridge et al. 2010, Bogosavlievich 2010, Nestor et al. 2011; Vanzella et al. 2012).

[a] Theoretical models use the *absolute* escape fraction of ionizing photons, i.e., the ratio between the number of escaping and produced ionizing photons (f^{LyC}_{ABS}=F(Lyc)^{obs}/F(Lyc)^{int}). In practice, we typically constrain the *relative* escape fraction ($f^{LyC}_{esc,rel}$), i.e., the ratio between the fraction of escaping LyC photons and the fraction of escaping photons at 1500A. f^{LyC}_{ABS} can be derived from observations of the LyC radiation and the extinction corrected Hα luminosity.

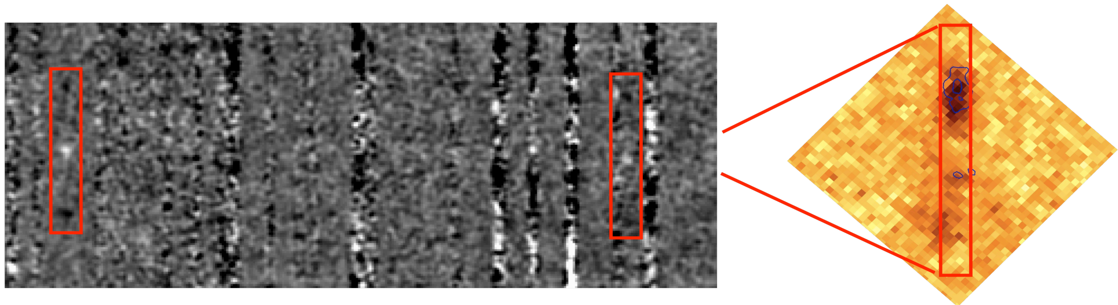

Figure 2: Left: The 2D K-band NIRSPEC spectrum of the candidate LyC emitter, MD32. Right: The rest-UV HST image of MD32 with the slit orientation shown. Faint [OIII] 5007 emission is seen at the expected redshift z=3.09. However, an additional line (spatially offset above the line on the slit) is seen at lower wavelength. Whether this line is from [OIII] 5007 or Hα, this indicates that the emission below 3700A is not LyC, but rather longer wavelength emission from a low-redshift interloper.

In the local universe, galaxies appear to be highly opaque to their own LyC. Upper limits have been presented for the few local galaxies studied to date[b] (Deharveng et al. 2001; Leitherer et al. 1995; Grimes et al. 2009). Statistics improve as the volume increases to z ~ 1, but in combined samples totaling over 600 galaxies, still no individual cases of LyC leakage are reported (Malkan et al. 2003; Siana et al. 2007, 2010; Cowie et al. 2009; Bridge et al. 2010). Stacking analyses on the various samples generally place upper limits on the escape fraction of a few percent (e.g., Bridge et al. 2010).

At redshift *z*~3 high escape fractions (~50% and higher) have been reported in about 10% of Lyman-break galaxies (LBGs, Shapley et al. 2006) and Lyα emitters (LAEs, Iwata et al. 2009; Nestor et al. 2011). In these results, the LAEs appear to be more strongly emitting in Lyman continuum, which is not surprising because the two UV features (LyC and Lyα) have high absorption cross-sections to both dust and HI. However, an inferred absolute f^{LyC}_{esc} of above unity in some cases (Iwata et al. 2009) makes these results difficult to interpret (Vanzella et al. 2012), and the lack of Ha accessibility limits further investigation. To complicate the issue more, none of the z>2.7 LyC leaking candidates followed up with high spatial-resolution imaging and spectroscopy has been confirmed (Siana et al. 2012a; see Figure 2). Similarly, the largest sample of LyC detections (Bogosavlievich 2010) is hard to interpret, due the unknown number of contaminated sources.

To reconcile the observed ionized Universe with the low measurements/limits of f^{LyC}_{esc}, it is possible that f^{LyC}_{esc} may evolve with redshift (e.g., Siana et 2010, Mitra et al. 2012; Haardt & Madau 2012, see Figure 3), and/or that f^{LyC}_{esc} may be higher in faint/low mass galaxies (e.g., Yajima et al. 2009, Nestor et al. 2011).

Yajima et al. (2011) studied the radiation transport of LyC in galaxies drawn from cosmological SPH simulations: at $z = 3 - 6$ they predict substantial LyC f^{LyC}_{esc} =8–20%) emission from galaxies with halo masses $M_{halo} <\sim 10^{10}$ M*, but little or nothing from more massive systems (Figure 1). Similar trends but with higher f^{LyC}_{esc} are reported by Razoumov & Sommer-Larsen (2010). f^{LyC}_{esc} is found to increase with decreasing metallicity and SFR – both of which are thought to positively correlate with M_{halo}. Alternatively, Conroy & Kratter (2012) attribute the higher escape fraction to the ability of high-velocity O-stars to escape the smaller galaxies at lower mass and higher redshifts. Moreover, because stars form more asymmetrically within the halo at low masses, f^{LyC}_{esc} is also found to depend on the particular line-of-sight to the

[b] Although see Leitet et al. (2011) for a debate regarding one potential low f^{LyC}_{esc} LyC emitting object.

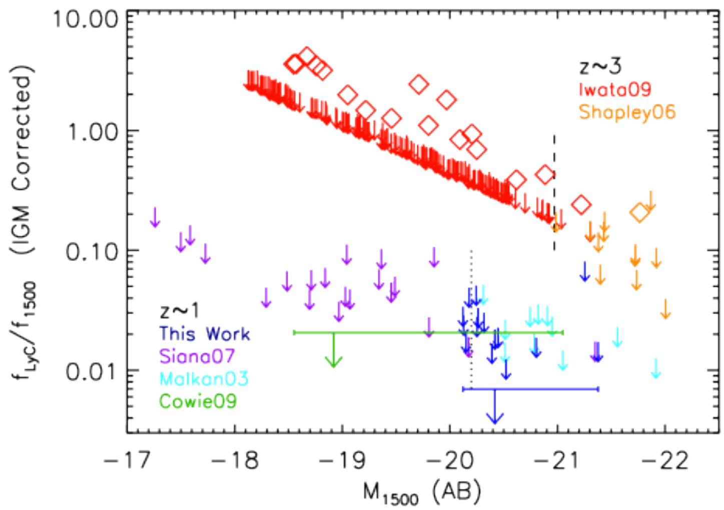

Figure 3: L_{yC}/f_{1500} measurements (versus UV luminosity) from several large surveys at $z \sim 1$ and $z \sim 3$ corrected for the average IGM attenuation at the relevant wavelengths.

galaxy. *All this suggests that high escape fractions and a variation with viewing angle may be found observationally in galaxies at the low mass end.*

Samples targeted for LyC studies at *z~3* mainly contain galaxies that are bright in the rest-frame UV (with L_{UV}>L*, Vanzella et al. 2010, Boutsia et al. 2011): with the current technology and at these redshifts, it is observationally challenging to reach relative $f^{LyC}_{esc,rel}$ of 50% in individual lower luminosity objects. Further progress even with HST will require very deep imaging such as CANDELS and UVUDF (Grogin et al. 2011, Tepitz et al. 2012) and will rely on rare, bright objects or the use of lensing magnification (see below; Vanzella et al. 2012, Siana et al. 2012b).

Lensing Magnification: We have recently obtained 33 HST orbits to study a dozen of known *z*~2.5 galaxies lensed by the well-studied massive cluster Abell1689 (Siana et al. 2012b). The galaxies have intrinsic luminosities well below L* (0.03L*<L_{UV}<L*), and the lensing magnification allows us to probe relative f^{LyC}_{esc} of ~40% in individual galaxies, comparable with the values typically reached in bright unlensed galaxies. We identified one galaxy with escaping ionizing radiation. Spectroscopic observations exclude the possibility of foreground contamination (see Figure 4). This galaxy has a stellar mass of only 3×10^7 M_{sun}, supporting the idea that LyC photons are coming from the smallest, rather than the brightest galaxies.

Constraining f^{LyC}_{esc} in dwarf galaxies with new telescopes: scaling from the current technological limit

A clear physical picture seems to be emerging in which the metagalactic ionizing field is fueled by the more abundant low-mass galaxies. With current technology, we can constrain the escape fraction in dwarf galaxies only through the magnification provided by gravitational lensing.
Although lensing is -and will be for the next decade- the only way to study intrinsically faint sources at redshifts *z>2,* these studies will be limited by the small sample size, due to the very small volumes magnified even by the most massive clusters. Moreover, uncertain cluster magnification factors introduce some level of uncertainty in the intrinsic luminosity/mass of the lensed galaxies. Also, interpreting any detection of LyC photons requires making an assumption about the IGM absorption, which we can currently only apply as an average correction.

Overcoming these limitations will require improved technology and/or much larger telescopes.

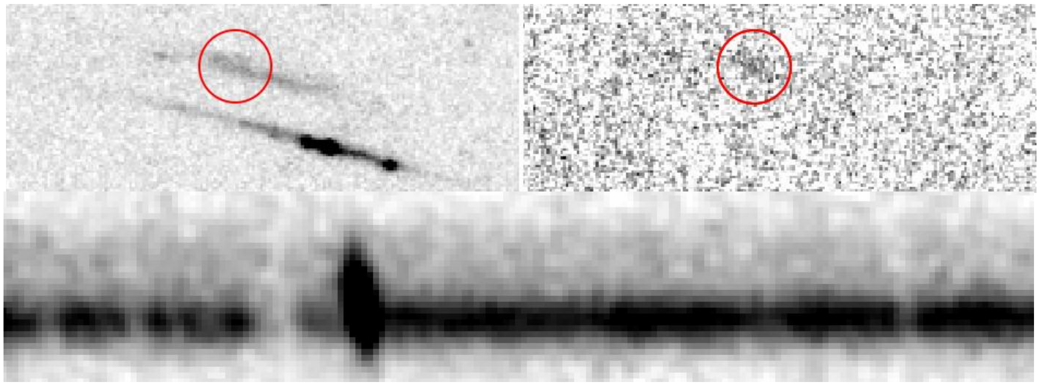

Figure 4 LyC escaping radiation from a dwarf galaxy at z~2.5. Top: the left panel shows the V band of two galaxies at z=2.51, while the right panel shows the UV image, sampling the LyC region at this redshift. Bottom: two dimensional spectrum of the galaxies, obtained with Keck. Both objects show common absorption lines and Lya in emission at the same redshifts (Siana et al. 2012).

In the next section, we discuss the IGM question, but for the moment we will look at where we stand with regards to detecting LyC emissivity in large samples of dwarf galaxies versus where we need to be.

We need to be able to measure LyC in unlensed dwarf galaxies at z<2.5 for three reasons: (1) to obtain necessary number statistics; (2) to remove the uncertain magnification factor; (3) to acquire spatially resolved LyC images without relying on (approximate) lensing reconstruction methods, (4) to reduce the rate of contamination by foreground objects.

Looking at the detailed numbers for the first lensed dwarf galaxy observed with escaping LyC radiation (Figure 4) perfectly illustrates the point. The object has a NUV[F275W] magnitude – which probes the rest frame LyC at z=2.5– of 26.9 (AB, detected at a significance of 5s in 33 orbits), and has a magnification factor of 82. The demagnified NUV magnitude for this galaxy is therefore 31.7(AB).
HST is the only UV telescope currently available with the required spatial resolution and filter set for this study. Detecting this galaxy without the aid of the lensing magnification would require a much longer integration, even though removing the spatial broadening effect of the lensing would improve the sensitivity. We would need to detect a compact object at AB~32. We know from the deepest HST exposures (Siana et al. 2012, Teplitz et al. 2012) that in about 30 orbits we can reach AB~29.5, thus requiring a factor of 10 improvement. With HST, reaching AB~32 would take 100 times the exposure time, accounting for the necessary correction for charge transfer inefficiency.

Although the WFC3-UVIS+F275W combination offers the best compromise between telescope/camera transmission and redshift coverage for LyC studies, observations with this setup are severely limited by the low overall transmission (the telescope + camera + filter peak throughput is 13%), the high read-out-noise (3e$^-$), and the poor charge transfer efficiency of CCDs in a high radiation orbit.

Given the current limit of the deepest NUV HST observations, it is reasonable to expect that a telescope of comparable collecting area to the HST, but with a substantial improvement in detector/filter characteristics, would allow us to push the deepest images to NUV~31. Given the uncertainties in the magnification factor quoted above, this depth will be sufficient to perform the crucial direct measurement of the escape fraction in unlensed dwarf galaxies. Furthermore, one could envision the use of NUV medium band filters –as opposed to the broad-band filters currently available on the HST– to isolate the wavelength range where most of the ionizing radiation is emitted. Because the escape of the ionizing radiation is predicted to vary depending on the particular line-of-sight to the galaxy, large samples of galaxies will need to be observed. Clusters can magnify rather small volumes, while a blank field, observed with a large field-of-view camera (a few times the current WFC3) could observe a large number of dwarf galaxies simultaneously.

Constraining f^{LyC}_{esc}: remove the last uncertainty with next generation space telescopes

With a new UV-optimized HST-size telescope we could directly measure the escape fraction in large samples of unlensed dwarf galaxies. However, the measurement would still be affected by the completely unknown contribution of the IGM absorption toward the specific line of sight to the galaxy. Moreover, to be able to extend the z~1 results to the reionization epoch (where f^{LyC}_{esc} cannot be measured directly), we will also need to measure the physical properties of the ionizing galaxies, in order to identify the mechanisms allowing a large ionizing escape fraction in some of them. Properly correcting for IGM absorption and studying the galaxies' properties will require deep UV spectroscopy (possibly with multiplexing capabilities).

In current f^{LyC}_{esc} measurements, any measured flux below the Lyman limit is corrected for using an average absorption due to the intervening IGM. This correction depends on the wavelength range covered (i.e., on the volume probed) by the filter used to measure the ionizing emissivity. Although the averaged IGM transmission is well determined observationally, the amount of attenuation along any specific line-of-sight is stochastic in nature, due to the absorption from rare Lyman Limit systems (LLSs). With high-resolution (R>5000, Songaila 2004) spectroscopy in the rest-frame 800-912Å of the LyC emitting galaxy, the presence of nearby absorbers could be identified, and the correction could be determined for the specific line-of-sight to each galaxy. This goal is obviously ambitious, and will require a substantial increase in aperture size for the next generation space-based telescopes.
Deep NUV spectroscopy covering the rest frame ~1800 Å will also be essential to measure absorption and emission line diagnostics useful to determine the physical conditions of the galaxies' ISM (including gas metallicity, kinematics, and stellar population properties). The detailed UV view will be perfectly complemented by IR spectroscopy with JWST that will cover the rest frame optical of these galaxies.

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SCIENCE FROM IGM/CGM EMISSION MAPPING

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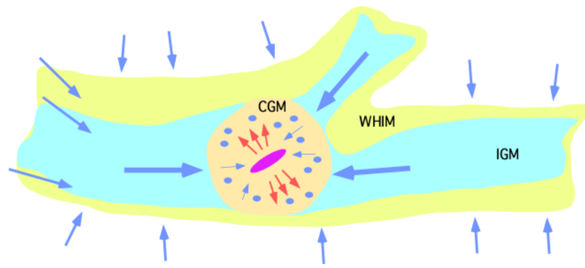
PROBING BARYONIC STRUCTURE FORMATION USING IGM MAPPING

NASA Balloons and Explorers [1, 2] have opened an age of precision cosmology by mapping the Cosmic Microwave Background. At the same time the processes that built cosmic structure and the galaxies that trace it are unknown. Models predict that the dark matter seeded by primordial quantum fluctuations formed the architecture of the Universe, a "cosmic web" of sheets and filaments of dark and normal (baryonic) matter. As the Universe expands, denser regions of dark matter collapse to form "dark halos", becoming much denser than average (and therefore characterized by the "overdensity parameter" δ the local density normalized by the average cosmic density). Dark halos have δ~200, and the dark matter cannot further collapse because it has no way to release gravitational energy. A fraction of the baryonic matter falls into these halos out of the cosmic web, fueling the formation and growth of galaxies over time. In order to form galaxies, baryonic matter must condense by more than 10 million times further, an extraordinary transformation that is extremely difficult to model with equations or even with large computer simulations, because of the complexity of the processes involved. Baryons, unlike dark matter, can convert the gravitational energy gained in this collapse from heat to cooling radiation. They must do so to collapse further, but this formative process is complex.



	Component			
Property	**Cosmic Web**	**Web/ Halos**	**Dark Halos**	**Galaxies**
Baryon & structure tracer	IGM *fuel*	WHIM *baryons metals*	CGM *infall winds metals*	*XUV disk gal. winds, SF*
δ	1-100	1-100	10^2-10^5	$>10^6$
Size [Mpc]	0.3-30	1-30	0.1-0.3	0.03-0.1
T[K]	10^4-10^5	10^5-10^7	10^4-10^6	
QSO absorption	Lα forest	OVI, broad Lα	Ly limit Metal lines	Damped Lα
Emission	Photon pumping (PP)	Collisional excitation (CE), PP	CE, PP, Lα fluorescence	UV cont CE from feed-back
Intensity [LU]	1-100	1-100	10^2-10^4	

Figure 1: *IGM/CGM emission probes all these components of the IGM, yet to be mapped.*

Baryons forming and fueling galaxies continue their catastrophic collapse by another 6-10 orders of magnitude to form molecular clouds and a further 12 orders of magnitude to become stars. These remarkable events, while complex, at least have a long history of study using a cornucopia of observational probes. The most massive stars formed produce energetic stellar winds and supernova explosions, which inject energy and heavy elements formed by fusion in their cores back into the galaxy's interstellar medium (ISM), the galaxy's halo, and the surrounding IGM. These "feedback" processes are very poorly understood, and may even control the infall of new fuel, yet they are essential to models that correctly predict fundamental properties such as the size, angular momentum, and luminosity function of galaxies and the physical connection between galaxy and dark halo properties.

Observers primarily use large galaxy surveys for mapping structure and galaxy evolution at low and high redshift. But galaxies represent less than 1% of the mass and only 10-20% of the baryons! The IGM hosts the majority of baryons, and plays a central role in the growth of structure and the evolution of galaxies. Yet our view of the IGM is based largely on the powerful but restricted information from QSO absorption line studies.

A Tour of the IGM. We summarize the physical components of the IGM, their relationship to galaxies, and their observational signatures in Figure 1. The picture we paint is inferred from QSO absorption line spectra (see [3] for a recent census), but has never been demonstrated with emission maps.

IGM and WHIM: Most of the web is moderate overdensity ($1<\delta<100$) gas ionized by the metagalactic UV background (UVB), and continuing to expand with the Hubble flow. Trace HI in the cosmic web is responsible for the Lyman α "forest" observed in QSO absorption line spectra. The forest is a powerful constraint on large-scale structure and cosmology, since simulations show that IGM baryons trace dark matter. There are metals in the cosmic web, suggesting early and on-going enrichment by galactic winds. At z=0 we suspect most baryons have collapsed into a Warm-Hot Intergalactic Medium (WHIM, $T_{vir}\sim10^5$-10^7K,) which produces weak, broad, difficult to detect Lyα absorption, and most of the z~0 OVI absorption.

CGM: Galaxies and groups form in dark matter halos ($\delta>100$) that form in the denser parts of web filaments and their intersections. We call the uncollapsed gas in halos the "Circum-Galactic Medium" (CGM). This gas may be infalling from filaments, cooling and collapsing onto the galaxy to fuel on-going star formation, stripped from merging subunits, or ejected and heated by galactic winds. CGM gas produces Lyman limit absorbers ($N_{HI}>10^{18}$ cm^{-2}), metal line absorbers (MgII, CIV, some OVI), and possibly Damped Lyα systems (DLA; $N_{HI}>10^{20}$ cm^{-2}).

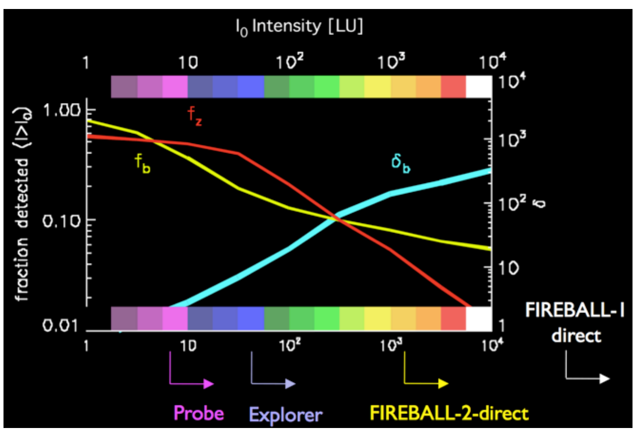


***Figure 2**. Estimated IGM Lyα emission line intensity vs. baryon overdensity δ_b (cyan curve). Fraction of baryons with Lyα intensity above I_0 (f_b: yellow curve), and fraction of metals with OVI1033 line intensity above I_0 (f_z: red curve). Intensity color scale is same as shown in Figure 3 and 4. Limits for direct detection also shown.*

Need for IGM Mapping There has been a long and productive effort to probe the IGM using QSO absorption lines and in X-ray emission in clusters. But the diffuse IGM that spans the vast majority of cosmic space, and the CGM occupying dark halos at the interface of galaxies and the IGM, remain invisible except in the shadow of sparsely distributed QSOs. There is growing evidence, from absorption line studies and from models, for a fundamental coupling of galaxies and the IGM, and the power of the IGM to probe cosmology. There is a compelling need to invent a new tool to explore the Universe, to discover and map emission from the IGM.

Emission from the IGM and CGM, while tenuous, can and will be detected by space-based spectrometers. In Figure 2 we show how the intensity of Lyα scales with overdensity δ, a good redshift-independent predictor of intensity. We also expect to detect OVI1033, CIV1549, and several other strong metal line species in CGM and WHIM. The physics of the predictions, particularly for the IGM, is straightforward and robust.

THE ROLE OF IGM/CGM EMISSION MAPPING IN UNDERSTANDING BARYONIC STRUCTURE FORMATION: FIRST IGM EMISSION MEASUREMENTS

The overarching question that can be addressed by IGM emission mapping is fundamental: ***"How does baryonic matter collapse, cool, form and fuel galaxies over cosmic time?"*** While the road to this answer may be tortuous, IGM emission mapping will provide a new perspective that could lead to fundamental breakthroughs by addressing these questions:

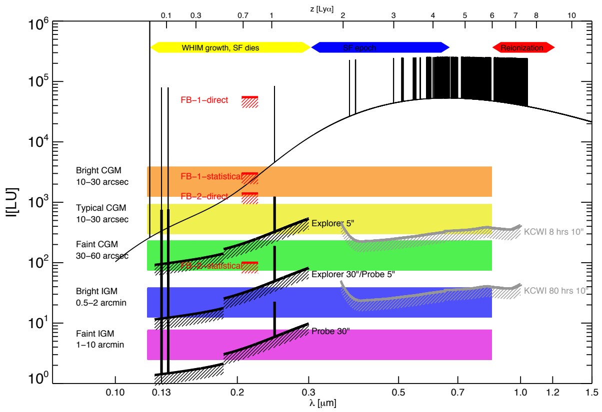


Figure 3: *Typical emission line strengths for Lyα from the CGM and the IGM. Bands show IGM emission levels, red: bright CGM, yellow: typical CGM, green: faint CGM, bright filaments, pink: faint filaments. Black curve shows typical sky background. Hatched lines show typical sensitivities for a range of feature size and exposure for UV experiments such as FIREBALL (red); Explorers and Probe-class missions (black).*

How strong is IGM emission, what is its relationship with absorption, and can emission mapping offer a new and powerful cosmological tool? The potential of IGM mapping can only be settled by detecting the emission, establishing its origin in the IGM and CGM (in contrast to star forming galaxies), and determining the typical emission strengths in various regimes. Detection and mapping require *excellent diffuse sensitivity* that is likely only obtained from dedicated instruments and/or missions. It is possible the first detections and preliminary characterization will come from Balloon and/or Explorer class missions with survey sensitivities of ~100-1000 LU over ~5 arcsec scales. Detailed mapping of multiple metal lines over a large cosmic volume will require the ~10-100 LU sensitivities of a Probe or even flagship mission instrument, which can also be used to detect and map the most diffuse filaments of the cosmic web. The fainter (~10-100 LU) but more extended (~30 arcsec) emission from filaments may also be detected by statistical means (stacking and/or cross-correlation with large-scale structure traced by galaxies) using surveys of narrowband 2D-imaging- and multi-object spectroscopy.

What is the total baryon content of the dark matter halos hosting galaxies in a 10^4-10^6K phase, and how does this gas content vary with redshift, galaxy type, evolutionary stage, and halo mass and environment? How does gas flow from the IGM into the CGM, and ultimately into galaxies to fuel ongoing galaxy formation, evolution and star formation? How do galaxies feed matter, energy, and metals back into the CGM, possibly regulating inflow and cooling? These are the missing links between the evolution of the IGM, dark halos and galaxies. There is exciting evidence from absorption line studies that extended zones of hydrogen and metals around galaxies exist [4, 5, 6, 7]. But there are almost no observational constraints on how CGM gas reservoirs are linked to the accretion of gas that fuels new star formation. We have no true maps, although there is tantalizing evidence for emission from CGM gas from Lyman Break Galaxies at z~1-3 [e.g., 8, 9] at levels of 10,000-50,000 LU. The as yet undetectable flow of baryonic matter from the cosmic web into galaxies may have been responsible for the epoch of star formation over 1<z<4. A major objective of IGM/CGM emission detection and mapping is to determine, by comparison with CGM emission at higher and lower redshift, whether the cessation of the delivery of fresh fuel explains the catastrophic fall in cosmic SFR in recent times.

How much CGM gas is inflowing to the galaxies, outflowing due to winds or AGN, replenished by inflow from the IGM? Do these gas flows regulate SF history, or are they regulated by star formation?

Map inflows. While CGM physics is more complex than IGM physics, the emission is brighter. Modern simulations have the mass and spatial resolution to trace the flow of mass and energy on scales that can resolve the CGM, but the models are in desperate need of observational input. We can compare the observed distributions of the various lines to CGM models with different assumptions. One goal is to determine the rate at which gas in the halo reservoir is accreting onto the central galaxies. By observing cooling radiation in IGM emission lines, we can detect mass fluxes as low as ~1$M_\odot$ yr^{-1}, a level that can strongly impact the evolutionary path of galaxies.

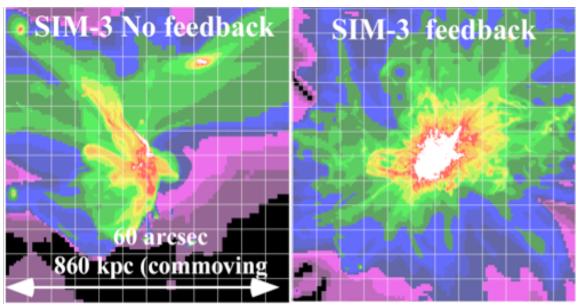


***Figure 4:** Feedback has a profound effect on Lyα emission z~0.7 from the CGM. See Fig. 3 for intensity vs. color code. Grid shows typical pixel size (5") for possible UV integral field spectrometers. Simulation from Greg Bryan, Columbia University.*

Map outflows. One of the central missing elements in galaxy evolution models is an accurate physical understanding of the effects of stellar and AGN feedback. Feedback causes mass and energy to flow out of galaxies and into the CGM, driving CGM gas from one phase to another, modifying cooling times and inflow mass flux and enriching the CGM. Feedback is constantly invoked to solve outstanding problems in galaxy formation theory [e.g., 10]. Galactic winds at z~3 must have a profound impact, since every solar mass of stars formed results in a comparable mass ejected into the CGM at 500-1000 km/s! Over a 10^8 year lifespan a typical starburst galaxy will deposit $10^{59.5}$ ergs into the surrounding medium, out to hundreds of kiloparsecs. Rest UV emission sensitively maps radiative shocks and multiphase gas, and probes the flow of gas, energy, and metals into the CGM. If only 1% of the wind energy is radiated in the UV, CGM regions will glow with a Lyα intensity of 1000LU. Feedback produces profound differences in the CGM emission morphology and kinematics (Figure 4). CGM emission mapping with velocity resolution ~60 km/s will measure CGM velocity dispersion and kinematic profiles, crucial for distinguishing inflows from outflows. Outflows will be probed by making controlled comparisons between the halos of similar masses with different galaxy SFR.

Science Measurement Requirements for IGM/CGM Emission Mapping

To achieve these objectives, IGM/CGM emission mapping requires diffuse **UV sensitivity**, 5-200LU **[R1; see Table 1]** to discover and map IGM/WHIM emission that probes a significant fraction of IGM baryons in the diffuse cosmic web **[O1]**. In order to discover and map CGM emission **[O2]** in Lyα, sensitivities of 100-5000LU are required. To detect and map metal lines such as CIV1549Å, OVI1033Å, CIII977Å, etc., sensitivities of 10-500LU are needed.

Mapping requires **imaging spectra of 2D regions [R2a]**. 3D maps (2 spatial x 1 redshift) of IGM emission are needed to assess size, density, mass, luminosity, and other key physical parameters of the IGM **[O1, O2]**, and to disentangle the spatial and physical relationships between the IGM, galaxies, and QSOs **[O1-O3]**.

IGM/CGM emission mapping also requires **multi-object spectroscopy [R2b]** in order to survey IGM filaments over their typical sizes **[O1]**, to obtain a statistically robust sample of CGM regions **[O2]**, and to provide a robust set of integrated galaxy spectra to relate to 2D IFS spectra. We require 2D spectroscopy surveys that **sample a large cosmic volume** >10,000 Mpc^3 **[R3],** ideally in a few contiguous fields, in order to map a representative sample of 10's of IGM/CGM emission regions with cosmic variance <30% in the baryon measurement. Multi-object surveys are required to probe x10 larger volumes (>100,000 Mpc^3 **[R3]**) in order to survey enough CGM regions to connect CGM to galaxy/halo physical properties (e.g., galaxy stellar, gas, and halo mass, star formation rate, and morphological type) in a statistically robust way.

It is essential to observe hydrogen and metal resonance lines (Lyα, OVI1033, CIV1550, CIII977, etc.) simultaneously to derive line diagnostics over a **broad redshift range (0.05<z<1.5) [R4]** to map IGM, CGM and the circum-QSO medium (CQM) during the epoch of cosmic star formation (z~1) and to provide a local baseline **[O1-3]**. Emission lines observed in CGM regions with complementary absorption line probes will provide even stronger diagnostics of the phase and filling factor of the halo gas. **Velocity resolution** of 50-100 km/s [**R5]** is required to obtain velocity profiles and sufficient centroid accuracy for kinematic mapping of inflows and outflows **[O2bc]**, and optimal detection of IGM emission **[O1bc]** separated from foreground continuum and line emission from the earth and Galactic ISM. Similarly, the **spatial resolution [R6]** we require to map CGM components and distinguish them from the central galaxies (5-35 kpc physical scales, 0.2<z<1.2) **[O23bc],** is accomplished with a 2D angular resolution of 1-5 arcsec.

UV emission-line mapping can obtain optimal, sky-limited diffuse emission-line sensitivity (**R1**) given **excellent rejection of unwanted signal.** Contrasts for IGM/CGM emission signals are typically 1-30% of Solar System and Galactic ISM foregrounds (zodiacal light, diffuse Galactic light, molecular hydrogen fluorescence, high ionization ISM emission).

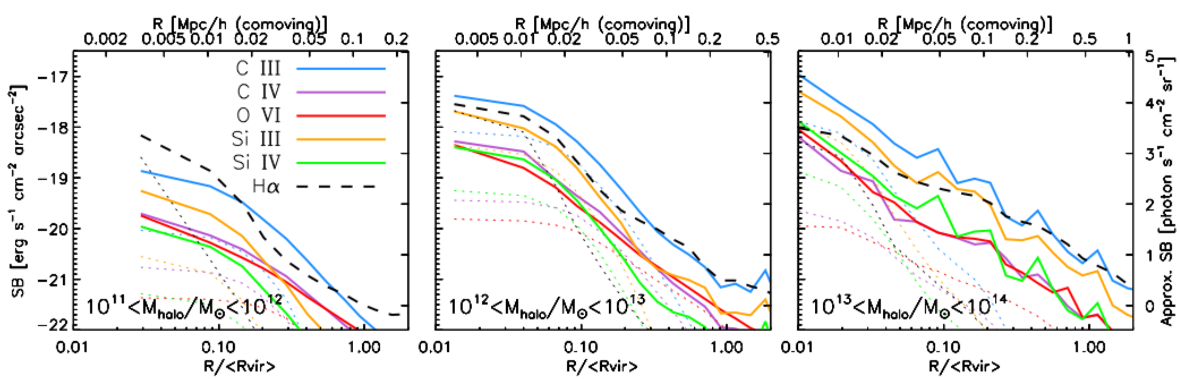


Figure 5. Metal line predictions for typical CGM regions at z=0.25 [van der Voort and Schaye, 2012; ref. 11]. *Three panels show three halo masses, profiles ranging from 0.01-1.0 of the virial radius. Detecting and mapping multiple metal lines will require sensitivities ~10-100LU on ~1-5 arcsec scales. Very faint emission at outer radii can possibly be detected using imaging spectroscopy and radial binning.*

Table 1. IGM/WHIM/CGM Emission Science Goals and Requirements

NASA Science Goal	**N1.** Understand the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today.	**N2.** Understand the origin and destiny of the Universe, and the nature of black holes, dark energy, dark matter, and gravity
New Worlds New Horizons Key Science Question	**A1.** How do baryons cycle in and out of galaxies and what do they do while they are there? **A2.** What are the flows of matter and energy in the circumgalactic medium?	**A3.** How do cosmic structures form and evolve? **A4.** What are the connections between dark and luminous matter?

IGM Emission Roadmap	**Discovery and Preliminary Characterization of Emission from the IGM, WHIM, CGM, CQM**	**Physical Properties of the IGM, WHIM, CGM, CQM**	**Tracing Baryon Structure Formation using IGM and CGM Emission**
Map IGM/WHIM [N1, N2, A3, A4]	**O1a. Discover IGM emission** from the hidden baryons in the Universe. Preliminary mass census.	**O1b. Characterize IGM emission** from the hidden baryons in the Universe. Mass census.	**O1c. Exploit IGM emission** to map baryonic structure formation in cosmic web
Map CGM [N1, A1, A2]	**O2a. Discover CGM emission** to explore IGM-galaxy co-evolution	**O2b. Characterize CGM emission** to determine physical conditions, gas flows and reservoirs	**O2c. Deep, multi-object surveys of galaxy/CGM emission regions** to explain IGM-galaxy co-evolution
Map Circum-QSO Medium (CQM) [N1, N2, A1-A4]	**O3a. Discover CQM emission** to explore QSO gas environment.	**O3b. Characterize CQM emission** to determine physical properties of QSO gas environment.	**O3c. Deep maps of multiple QSO CQM reqions** to determine how QSOs are formed and evolved, and in what environments.
Surveys	**Moderately deep imaging and multi-object spectroscopic surveys** of 10-100s of halos/galaxies and filaments.	**Very deep imaging and multi-object spectroscopic surveys** of 10-100's of objects and filaments.	**Wide, deep imaging and multi-object surveys** of 100-1000's of halos, filaments, and regions.
R1. Diffuse UV sensitivity: (LU = ph cm^{-2} s^{-1} sr^{-1})	IGM 10-200 LU (5 arcsec). CGM: 100-5000 LU (5 arcsec)	IGM: 5-100 LU (5 arcsec). CGM: 100-5000 LU (2 arcsec)	IGM 5-100 LU (5 arcsec). CGM: 100-5000 LU (1 arcsec)
R2a. Spectral Mapping (IFS): Contiguous survey regions	Field of view: ~4x4 $arcmin^2$	Field of view: ~2x2 $arcmin^2$	Field of view: ~2x2 $arcmin^2$
R2b. Spectral Mapping (MOS): Wide-field, multi-object mapping of galaxies and their CGM halos. Wide-field surveys of filamentary emission from cosmic web.	Field of view: (10-20) x (10-20) $arcmin^2$	Field of view: (2-5) x (2-5) $arcmin^2$	Field of view: (2-5) x (2-5) $arcmin^2$
R3. Cosmic volume (at low z)	IFS/MOS: 10^4 / 10^5 Mpc^2	IFS/MOS: 10^4 / 10^5 Mpc^2	a) IFS/MOS: 10^5 / 10^6 Mpc^2
R4. Spectral range	Observe Lyα, OVI1033, CIV1550 over $0.2 < z < 1$	Observe Lyα, OVI1033, CIV1550 over $0.2 < z < 1$	Observe Lyα, OVI1033, CIV1550 over $0.05 < z < 1.5$
R5. Velocity resolution	100-300 km/s	50-100 km/s	50-100 km/s
R6. Spatial resolution sufficient to resolve CGM components from central galaxy (~5-20 kpc)	20-40 kpc (~5 arcsec)	10-20 kpc (~3 arcsec)	3-7 kpc (~1 arcsec)

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Project Lyman: Quantifying 11 Gyrs of Metagalactic Ionizing Background Evolution

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Executive Summary.
The timing and duration of the reionization epoch is crucial to the emergence and evolution of structure in the universe. The relative roles that star-forming galaxies, active galactic nuclei and quasars play in contributing to the metagalactic ionizing background across cosmic time remains uncertain. Deep quasar counts provide insights into their role, but the potentially crucial contribution from star-formation is highly uncertain due to our poor understanding of the processes that allow ionizing radiation to escape into the intergalactic medium (IGM). The fraction of ionizing photons that escape from star-forming galaxies is a fundamental free parameter used in models to "fine-tune" the timing and duration of the reionization epoch that occurred somewhere between 13.4 and 12.7 Gyrs ago (redshifts between 12 > z > 6). However, direct observation of Lyman continuum (LyC) photons emitted below the rest frame H I ionization edge at 912 Å is increasingly improbable at redshifts $z > 3$, due to the steady increase of intervening Lyman limit systems towards high z.

Thus UV and U-band optical bandpasses provide the only hope for direct, up close and in depth, observations of the types of environment that favor LyC escape. By quantifying the evolution over the past 11 billion years ($z < 3$) of the relationships between LyC escape and local and global parameters such as: metallicity, gas fraction, dust content, star formation history, mass, luminosity, redshift, over-density and quasar proximity, we can provide definitive information on the LyC escape fraction that is so crucial to answering the question of, how did the universe come to be ionized? Here we provide estimates of the ionizing continuum flux emitted by "characteristic" (L^*_{uv}) star-forming galaxies as a function of look back time and escape fraction, finding that at $z = 1$ (7.6 Gyrs ago) L^*_{uv} galaxies with an escape fraction of 1% have a flux of 10^{-19} ergs cm^{-2} s^{-1} Å^{-1}.

Keywords: Atomic processes, Ultraviolet, Galaxies, Ionizing background, Reionization

THE ESSENTIAL ROLE OF LYC ESCAPE

Some 0.3 Myr after the Big Bang, the adiabatic expansion of the universe caused the primordial plasma of protons and electrons to cool, creating a neutral gas. Recent observations show that most of the universe has since been reionized and provide constraints to the duration of this process. Sloan Digital Sky Survey spectra of luminous high-redshift quasars have black H I Gunn-Peterson troughs, indicating

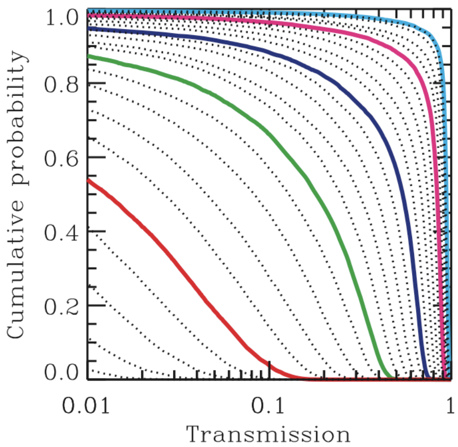

FIGURE 1. The results of a Monte Carlo [10] showing the effects of intergalactic absorption by Lyman limit systems on the transmission of LyC photons. The graph depicts the cumulative probability of having a line-of-sight transmission greater than that shown on the axis for LyC photons emitted between (880 – 910 Å). The light blue, magenta, dark blue, green and red are contours for the redshifts $z = 1$, 2, 3, 4 and 5 respectively. At $z = 4$, the probability of having a transmission of greater than 30% is 0.2

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a mean H I fraction of $\gtrsim 10^{-3}$ at $z \geq 6.4$ when the age of universe was ≈ 1 Gyr [1]. Evidence that reionzation started even earlier is provided by the polarization of the microwave background on large angular scales seen by the Wilkinson Microwave Anistropy Probe, which is consistent with an ionization fraction $\sim$ unity at $z \approx 11$ when the universe was ≈ 365 Myr old [2].

Complete reionization occurs when the rate of ionizing photons emitted within a recombination time exceeds the number of neutral hydrogen atoms. The duration of the reionization epoch depends on the initial mass function (IMF) of the first ionizing sources, their intrinsic photoionization rate (Q), the baryon clumping factor ($C \equiv <\rho^2> / <\rho>^2$), and the fraction of ionizing photons that somehow manage to escape into the intergalactic medium (IGM) [3]. Of these parameters the LyC escape fraction (f_e) is the least constrained [1]. Its (often arbitrary) choice can alter conclusions regarding the nature and duty cycle of the sources thought to be responsible for initiating and sustaining reionization [4, 5].

LyC escape plays an essential role in the formation of structure. The escape fraction of ionizing photons from galaxies is the single greatest uncertainty in estimating the intensity of the metagalactic ionizing background (MIB) over time [6]. The MIB controls the ionization state of the IGM at all epochs and may be responsible for hiding a non-trivial fraction of the baryons in the universe [c.f. 7, 8]. Ionizing radiation produced by star-forming galaxies is ultimately related to the rate of metal production by stellar nucleosynthesis [9]. The MIB intensity is a gauge of the feedback into the IGM of chemicals, mechanical energy and radiation by supernovae and stellar winds.

Ionizing radiation regulates the collapse of baryons on local and global scales [11]. Photoelectrons provide positive feedback for star formation by promoting the formation of H^-, which in turn catalyzes the production of H_2; a crucial coolant for collapse at high-z. Negative feedback occurs when photoionization heating raises the temperature and inhibits stellar collapse by increasing the Jeans mass. Photodissociation of H_2 is another form of negative radiative feedback mediated by both Lyman-Werner photons in the 912 – 1120 Å bandpass and LyC photons [12]. Whether ionizing radiation has a positive or negative effect on a collapsing body depends on the gas density, the strength of the radiation field, the source lifetime and the escape fraction of LyC photons[11, 13].

Quantification of the LyC escape fraction is at the frontier of reionization physics. The high opacity of even small column densities of H I to ionizing radiation makes the sources very faint at all epochs, but especially at redshifts $z \gtrsim 3$ [3]. Figure 1 from Inoue and Iwata [10], shows the likelihood of detecting LyC escape from star-forming galaxies becomes increasingly improbable above $z > 3$, due to a progressive increase with redshift in the number density of intervening Lyman limit and Lyα forest systems. Detections above $z > 4$, while not ruled out, will be extremely rare. This favors UV and U-band optical observations in efforts to directly identify and spatially resolve those physical environments that allow LyC to escape. By examining at low redshift the relationship between LyC escape and the local and global parameters of metallicity, gas fraction, dust content, star formation history, mass, luminosity, redshift, over-density and quasar proximity, we seek to understand how the universe came to be ionized.

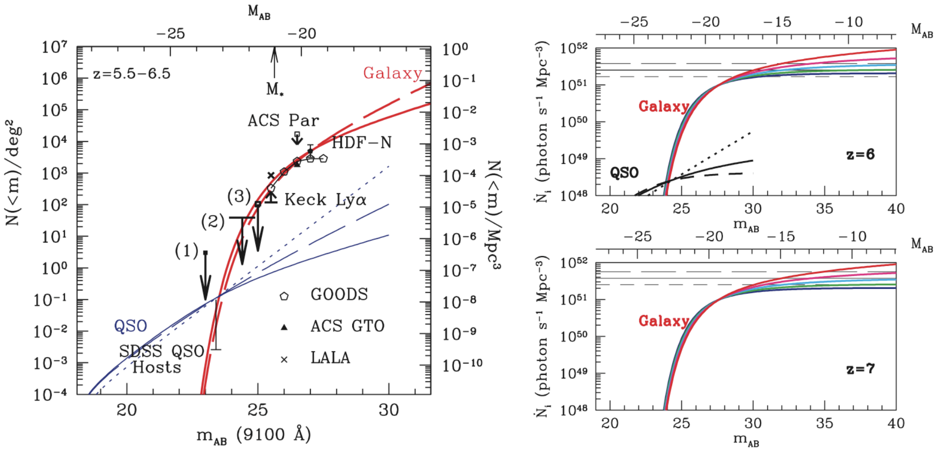

FIGURE 2. Left – LFs for quasars and galaxies at $z = 6$. Right – Reionizing photon production rate for quasars and galaxies at a redshift of $z = 6$ and for galaxies alone at $z = 7$. The production rate required to maintain a fully ionized universe for clumping factors of 20, 30 and 40 are indicated at the top of each graph. Higher clumping factors require more photon production. See [15] for details.

SOURCE(S) OF REIONIZATION AND THE MIB

The fundamental question is, how did the universe come to be reionized and how long did it take? Current thinking posits that LyC escape from the smallest galaxies powers reionization at $z \approx 6$, since quasars are too few in number to sustain reionization [3, 14, 15]. However, this conclusion depends on an extrapolation of the faint end slope of the galaxy luminosity function (LF, $-1.6 \leq \alpha \leq -2.0$), the faint end luminosity cutoff, the clumping factor ($3 < C < 45$) and escape fraction ($f_e \sim 0.1 – 0.8$).

The sensitivity of this conclusion to the faint end slope and the role played by the clumping factor and f_e is illustrated in Figure 2 taken from Yan and Windhorst [15]. On the left, the LFs for quasars and galaxies are displayed for a redshift of $z = 6$. Two extreme faint end slopes are shown for the galaxies (-1.6, -2.0) and for the quasars (-1.6, -2.6). On the right, two panels show the cumulative reionizing photon production rate for quasars and galaxies at a redshift of $z = 6$ and for galaxies alone at $z = 7$. Horizontal lines drawn at the top of each panel mark the critical production rate required to keep the universe fully ionized for clumping factors of 20, 30, 45 (higher clumping factors require more photon production to overcoming clump self-shielding) and assuming $f_e = 0.1$.

The figures show that at $z = 6$ the faintest galaxies dominate the LyC production and are more likely than quasars to maintain the universe in a fully ionized state. The case becomes less certain at $z = 7$ where it has been found that maintaining reionization requires either a "top heavy" IMF or escape fractions $0.3 \lesssim f_e \lesssim 0.8$, assuming $20 < C < 45$ [16, 17], although recent work by Finkelstein et al. [18] suggests $0.1 \lesssim f_e \lesssim 0.5$ and $3 < C < 5$. It may be that there are not enough star-forming galaxies early on to initiate reionization [19] and that mini-quasars might be involved [20]. There are also indications that the initiation of reionization above $z = 7$ may require a "hard" spectral energy distribution (SED) more characteristic of quasars [19].

Black holes reside in the nuclei of most if not all quiescent galaxies [21, 22], so it is simplistic to characterize reionization as a process caused by either quasars with $f_e = 1$ or star-forming galaxies with $f_e < 1$. Some fraction of quasars exhibit a break at the Lyman edge likely due to obscuration by host galaxies[23, 24]. The central engines of active galactic nuclei (AGN) have intermittent duty cycles, so the effects of previous AGN activity within an apparently dormant galactic environment may reduce, for a time, the local H I density aiding LyC escape. A quasar in close proximity to star-forming galaxies could produce a similar effect. Such considerations become increasingly important as the MIB budget moves from one dominated by star-forming galaxies near $z \sim 6$ to one with a quasar contribution that peaks at $z \sim 2$ [25]. Wide-field observation of f_e from objects in extended cluster environments can be used to map out the relative contribution of galaxies, AGN and quasars to the MIB in the local universe and provide a means to assess its spatial uniformity in the redshift range $z \lesssim 2.3$, which cannot be probed by the ratio of He II/H I Lyα forest lines [24].

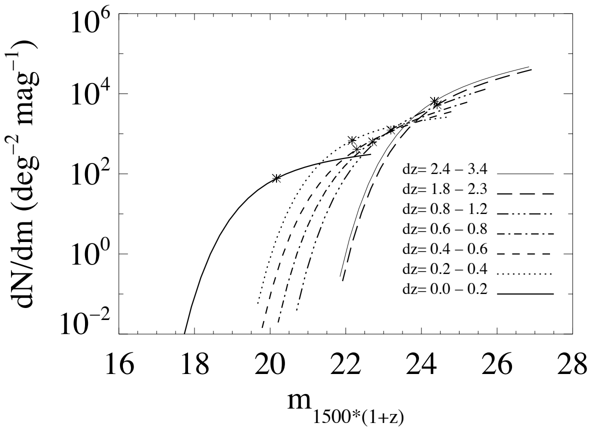

FIGURE 4. Surface densities as a function of observer's frame apparent magnitude for galaxy populations with redshifts between 0 – 0.2, 0.2 – 0.4, 0.4 – 0.6, 0.6 – 0.8, 0.8 – 1.2, 1.8 – 2.3, 2.4 – 3.4, estimated following Arnouts[35]. There are 100s – 10,000's of galaxies per square degree per magnitude with 24$> m^*_{1500(1+z)} >$ 20 for each redshift interval.

LYC AND LYα ESCAPE: ENVIRONMENTS, ANALOGS AND PROXY PROSPECTS

Reionization appears to require LyC leakage from galaxies with $f_e \sim 0.1$, but how LyC and Lyα escape from galaxies is somewhat mysterious. Most star-forming galaxies have mean H I columns greater than damped Lyα systems (DLA).The optical depth at the Lyman edge for DLAs is $\tau_{\lambda<912} > N_{HI}$ 6.3 x 10^{-18} $(\lambda/912)^3$ = 1260 $(\lambda/912)^3$, while at the line core of Lyα the optical depth is, $\tau_{Ly\alpha}$ = N_{HI} 6.3 x 10^{-14} = 1.26×10^7 (for V_{dop} = 12 km s^{-1}). Escape from such large mean optical depths requires that the interstellar medium (ISM) be highly inhomogeneous. The escape of Lyα (f_α) is aided by velocity gradients and the presence of multi-phase media [26, 27, 28, 29]. Similarly, LyC escape is thought to result from galaxy porosity, low neutral density, high ionization voids, chimneys created by supernovae or the integrated winds from stellar clusters [30],

Exploring the possibility of a proxy relationship between f_e and f_α will be extremely important in the coming decade as JWST seeks to identify the source(s) responsible for initiating and sustaining reionization. The brightness of Lyα emission from the first objects is expected to be much easier to detect than their rest frame UV continuum. Consequently, JWST will probably have to rely upon observations of Lyα escape as a proxy for LyC escape. Unfortunately there is no guarantee that such a proxy relationship exists, because escaping Lyα photons are created by recombining electrons freed by the LyC photons that do not escape [31] ([Ly$\alpha \approx (2/3)Qf_\alpha(1-f_e)exp(-\tau)$]). It is essential to test the proxy hypothesis at $z \lesssim 3$ by obtaining simultaneous observations of LyC and Lyα.

LYC ESCAPE DETECTIONS AND THE ADVANTAGES OF SPECTROSCOPY

Siana et al. [32] have provided the most current summary of detection efforts to date. In short they have returned mixed, but tantalizing results, that hint at a trend for f_e falling towards low-z. Spectroscopic observations hold an advantage over broad band imaging by providing the means to quantify ISM and IGM attenuation by H I using Lyman series absorption and investigating Lyα escape processes. Moreover, they provide the means to detect spectroscopically, absorption features from species with wavelengths shortward of the Lyman edge, as was reported by Bogosavljevic and Steidel [33] who found evidence for the O I λ 877 in a stack of 13 spectra of $z = 3$ galaxies. A quantitative assessment of the evolving contribution of galaxies to the MIB will likely require spectroscopic surveys over wide angular fields to acquire the large number of observations needed for establishing LyC luminosity function [34].

LYC DETECTION REQUIREMENTS

GALEX has shown there are thousands of far-UV emitting galaxies per square degree down to its limiting magnitude m$_{FUV}$ $\approx$ 25.McCandliss et al. [36] have suggested a wide field spectroscopy survey as an

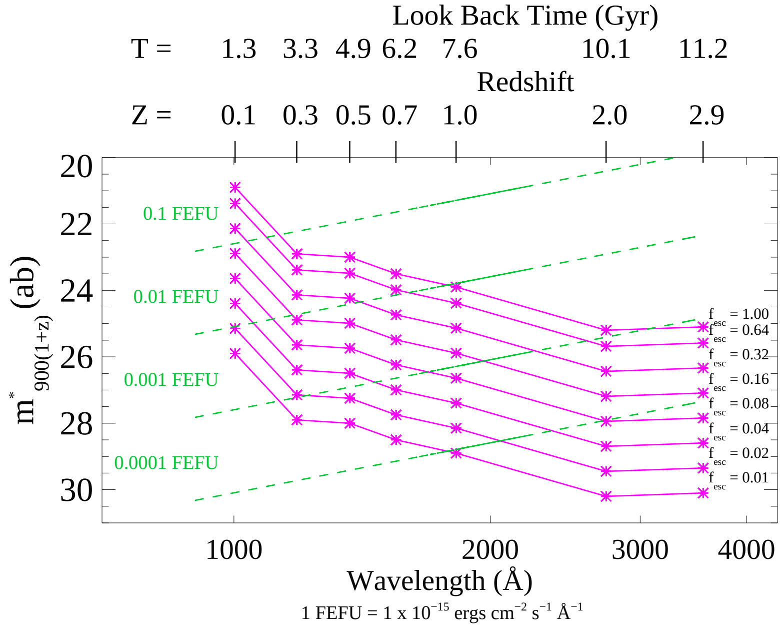

FIGURE 5. The purple asterisks show the characteristic apparent LyC magnitudes (ab) $m*_{900(1+z)}$ as a function of look back time, and in redshift and wavelength space, for different escape fractions. Contours of constant flux units are overplotted as green dashes marked in FEFU fractions; the background limit for *FUSE*. See [36] for details.

efficient way to search for LyC and Lyα leakage. Instrument requirements can be derived from the sensitivity required to detect LyC escaping star-forming galaxies over the redshift interval $0.02 \lesssim z \lesssim 3$.[1]

To estimate the sensitivity requirement we use the surface density of UV rest frame emitting galaxies as a function of apparent magnitude (observer frame flux) and redshift, Figure 4, where the LFs from Arnouts et al. [35], for the redshift intervals indicated in the caption, are shown. Each asterisk marks the characteristic magnitude of the LF, appearing in the Schechter function.

We convert the 1500 Å characteristic apparent magnitudes to LyC magnitudes using,

$$m^*_{900(1+z)} = m^*_{1500(1+z)} + \delta m^{1500}_{900} + \delta m_e, \tag{1}$$

with $\delta m_e = -2.5 \log f_e$ and $\delta m^{1500}_{900} = 2.5 \log (f_{1500}/f_{900})$. Starburst99 models[37] for continuous star-formation, assuming solar metallicity, a Salpeter IMF and an upper mass cutoff of 100 $M_\odot$, yield $f_{1500}/f_{900} \approx 2$. This ratio is insensitive to age with $1.5 \lesssim f_{1500}/f_{900} \lesssim 3$ for ages 10 – 900 Gyr. The apparent magnitude in the LyC, as a function of z for f_e = 0.01, 0.02, 0.04, 0.08, 0.16, 0.132, 0.64 and 1 are displayed in Figure 5 as a series of purple connected asterisks. Dashed green lines give the conversion from magnitude to flux units. We find that L^*_{uv} galaxies with f_e = 1% have LyC fluxes $< 10^{-19}$ ergs cm^{-2} s^{-1} Å^{-1} at look back times between 7.6 and 11.2 Gyrs ($1 < z < 3$).

CENTRAL QUESTIONS, PRIORITIZATION AND ENABLING TECHNOLOGIES

Understanding the mechanisms of reionization hinges on understanding how f_e changes as a function of luminosity and redshift. The answer will be important regardless of the outcome. If star-forming galaxies are found with $f_e \gtrsim 0.1$ then they become plausible sources of reionization. If not, then new physics may be required to explain reionization [38].

Four central questions of fundamental importance to the field can be addressed in the coming decade:

1. What are the relative contributions of quasars, AGN and star-forming galaxies to the MIB at $z \lesssim 3$.

[1] The lower limit is set by the need to work at redshifts high enough to escape the H I "shadow" of the Milky-Way.

2. What is the relationship between f_e and the local and global parameters of metallicity, gas fraction, dust content, star formation history, mass, luminosity, redshift, over-density and quasar proximity.
3. Do low-z analogs exist of the faint high-z galaxies thought to be responsible for reionization?
4. Can the escape fraction of Lyα photons serve as a proxy for f_e?

The answer to the last question is critical to the JWST key project seeking the source(s) of reionization.

These questions can be most efficiently addressed using ultra-sensitive wide field spectroscopic surveys from space to probe the ionizing characteristics of galaxies as old as 11 Gyrs. Key mission-enabling technologies that will support the development of $0.^{\circ}5$ field-of-view, multi-object UV spectroscopy include microshutter arrays [39], high efficiency aberration corrected dual-order gratings [40], large format detectors [41] and GaN photocathodes [42]. Future high-grasp UV telescopes sensitive enough to detect LyC leak will also easily detect the cosmic web of low surface brightness Lyα emission, providing an unambiguous beacon for emerging complexity [43, 44].

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Synergistic Astrophysics in the Ultraviolet using Active Galactic Nuclei

A Response to NASA/SMD Request For Information (RFI) on Science Objectives and Requirements for the Next NASA UV/Visible Mission Concepts (NNH12ZDA008L)

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Abstract: *Observing programs comprising multiple scientific objectives will enhance the productivity of NASA's next UV/Visible mission. Studying active galactic nuclei (AGN) is intrinsically important for understanding how black holes accrete matter, grow through cosmic time, and influence their host galaxies. At the same time, the bright UV continuum of AGN serves as an ideal background light source for studying foreground gas in the intergalactic medium (IGM), the circumgalactic medium (CGM) of individual galaxies, and the interstellar medium (ISM) and halo of the Milky Way. A well chosen sample of AGN can serve as the observational backbone for multiple spectroscopic investigations including quantitative measurements of outflows from AGN, the structure of their accretion disks, and the mass of the central black hole.*

Understanding how black holes accrete matter, grow through cosmic time, and influence their host galaxies is crucial for our understanding of galaxy evolution. Outflows from AGN, visible as blue-shifted ultraviolet and X-ray absorption lines from highly ionized species (Crenshaw et al. 2003), may be at the heart of feedback processes that regulate the growth of the host galaxy and chemically enrich its surroundings. The energy and momentum of outflowing winds from AGN expel gas from the host galaxy and inhibit star formation. In terms of color-magnitude diagrams, this ultimately moves AGN from the "Blue Cloud" across the "Green Valley" and onto the "Red Sequence" (Baldry et al. 2004). Shutting down further star formation limits galaxy growth, which is necessary to produce the observed galaxy luminosity function (Cole et al. 2001, Huang et al. 2003). The end result of AGN feedback couples black hole growth to galaxy growth, leading to the observed correlation between the mass of the black hole and the velocity dispersion of the spheroid of the host galaxy (M_{BH}-σ) (Di Matteo et al. 2005).

The central power source for AGN is accretion onto the central black hole through a luminous accretion disk. Most AGN emit their energy in the far and extreme ultraviolet energy range with a peak at ~1200 Å, extending into the extreme ultraviolet (Telfer et al. 2002; Shang et al. 2011). Temperatures forming such a peak are too cool for thermal radiation from the accretion disk to continue to the soft X-ray band (e.g., Done et al. 2012), and a likely explanation for the extreme ultraviolet continuum is Comptonization of the disk spectrum by a warm, ionized coronal layer just above the disk or near its inner edge. Direct observation of this portion of the spectrum in intermediate redshift AGN (z~1) and correlation with the longer-wavelength thermal continuum to study time lags associated with the Comptonized reprocessing would enable us to assess the geometry of the accretion disk.

The inferences summarized above have been gleaned from UV and optical observations of a few dozen, mostly local ($z < 0.15$), AGN. While current observations have enabled us to produce a general picture of AGN structure and how feedback might influence galaxy formation, we still lack firm quantification of accretion disk structure, the mass and energy flux in outflows, and the abundances in the outflowing gas. Models of AGN feedback usually include these inputs as parametric entries with little microphysics motivating the choices. Measuring such quantities in large samples of AGN over a range of redshift, luminosity and environment are necessary both to test models of galaxy formation, and supply the necessary physics. An 8-m UV telescope and spectrograph sensitive from 900—3200 Å could give sensitivity of 100x that of the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST), enabling observations of a sample an order of magnitude or more greater than the few AGN currently observed in detail.

In this paper we present some sample scientific programs that could be enabled by such a dramatic increase in sensitivity. Furthermore, each of these programs could be accomplished with well-chosen samples of AGN and observations that simultaneously satisfy the scientific objectives of other compelling scientific investigations.

Quantifying Outflows in Nearby AGN

An AGN outflow with a kinetic luminosity of 0.5% (Hopkins & Elvis 2010) to 5% (Di Matteo et al. 2005) of the Eddington luminosity of the black hole provides sufficient feedback to couple black hole growth to the evolution of the host galaxy. Measuring the kinetic luminosity of an AGN wind, however, is difficult. Assuming the outflow is in the form of a partial thin spherical shell moving with velocity v, its mass flux, $\dot{M}$, and kinetic luminosity, $\dot{E}_k$, are given by:

$$\dot{M} = 4\pi\Delta\Omega R N_H \mu m_p \mathrm{v}$$
$$\dot{E}_k = \tfrac{1}{2}\dot{M}\mathrm{v}^2$$

where $\Delta\Omega$ is the fraction of the total solid angle occupied by the outflow, R is the distance of the outflow from the central source, N_H is the total hydrogen column density of the outflow, m_p is the mass of the proton, and μ=1.4 is the molecular weight of the plasma per proton. Observations of UV absorption lines are the key to measuring all these necessary quantities.

For nearby AGN, the 900—3200 Å band contains key spectral diagnostics that let us measure the kinematics and abundance of highly ionized gas in the vicinity of the black hole. In particular, this wavelength range includes the Lyman lines of neutral hydrogen, and the lithium-like doublets of O VI, N V, Si IV, and C IV. High signal-to-noise observations of the absorption troughs of the Lyman series and these doublets allow us to measure ionic column densities and covering fractions as a function of outflow velocity in a model-independent way (Hamann et al. 1991; Arav et al. 1999). Combining ionic column densities with photoionization models yields the total column density and the ionization parameter. (An important additional product of the photoionization models is the absolute abundances of the elements in the outflow [Arav et al. 2007].) However, to determine the kinetic luminosity, we also need to determine the distance, R, of the outflow, which is linked to the gas density via the ionization parameter, $\xi = L_{ion} / nR^2$.

Measuring the gas density is the most difficult part of the observational problem. Density-sensitive transitions are one approach, but at low redshift, only low-ionization transitions of C II, C III, and Fe II are available. Since higher-ionization gas dominates the mass flux in the AGN winds (Crenshaw & Kraemer 2012), these are of limited utility. Nevertheless, the C III* λ1176 transitions have been used to establish the distance of outflow components in a few AGN (NGC 4151, Kraemer et al. 2006; NGC 3783, Gabel et al. 2005). A more generally applicable approach has been to monitor changes in the absorption components in the outflows and measure the timescale of their response to changes in the ionizing continuum, as shown in Fig. 1. The ionization/recombination timescales then give the density of the absorbing gas. Since this requires repeated high S/N observations, the method has been successfully applied to only the nearest and brightest AGN. Crenshaw & Kraemer (2012) give a summary of the best results for both techniques that comprises a total of only 10 objects.

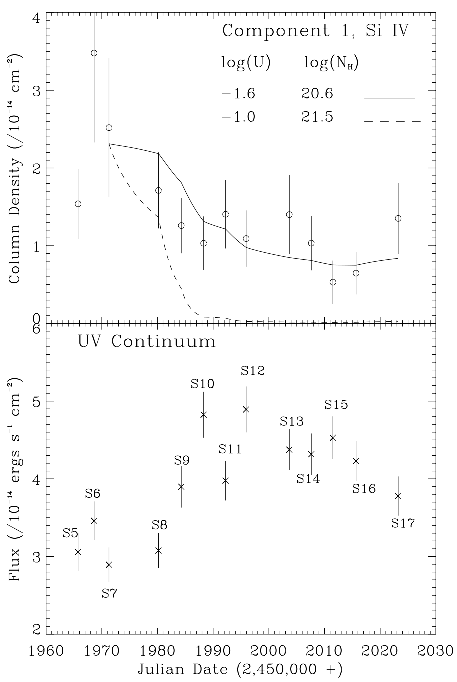


Figure 1: (Top) Variations in Si IV column density during the monitoring observations of NGC 3783 (Gabel et al. 2005). The solid line shows the best-fit solution based on simultaneously matching the low and high-state measurements. The dashed line shows a higher-ionization solution that fits only the low-state column densities. (Bottom) The UV continuum light curve is shown for comparison.

To make significant progress in quantifying AGN outflows in the local universe (z<0.15) requires the following:

1. High sensitivity (100x COS) covering 900—3200 Å to enable high S/N observations of outflow absorption signatures in the Lyman lines, O VI, N V, Si IV, and C IV. This would enable surveys of hundreds of AGN, which could be accomplished using the same sample of background sources used to probe the circum-galactic medium of intervening galaxies.
2. The same high sensitivity would enable repeated observations of a select subsample of AGN to measure the ionization response of the absorbers and thereby measure the density and distance of the absorbing gas. Such repeated observations could be part of a reverberation-mapping program that mapped the two-dimensional kinematics of the broad-line region in these same AGN. (See the white paper on reverberation mapping by Peterson et al. 2012.)

Outflows in AGN at Intermediate Redshift

At intermediate redshifts, 0.2 < z < 2.0, extreme ultraviolet absorption lines of other highly ionized species become visible in the 900—3200 Å band. Ne VIII λλ770,780, Mg X λλ610,625 and Si XII λλ499,521 probe gas at ionization levels comparable to the O VII and O VIII features commonly seen in X-rays from local AGN. These ions have ionization potentials comparable to the X-ray absorbing gas detected in O VII and O VIII in bright, local AGN (which dominate the mass and kinetic energy flux, Crenshaw & Kraemer 2012). These UV ions have currently only been detected in the brightest intermediate-redshift AGN (Telfer et al. 1998; Muzahid et al. 2012). At intermediate redshifts, higher-ionization density-sensitive lines are redshifted into the

UV. Pairs of density-sensitive, ground+excited transitions of O III, O IV, O V, and Si IV become visible above redshifts of a few tenths, and they enable the direct measurement of the density in high-ionization gas in a single observation, as demonstrated by Arav et al. (2012) (see Fig. 2).

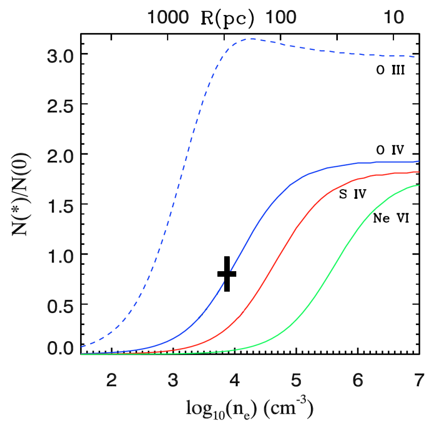


Figure 2: Outflow distance diagnostics for high ionization outflows. We first determine the electron number density (n_e) by measuring the column density ratio between the excited and ground state energy level of a given ion. The expected curves are shown here for 4 ionic species. For component A in HE0238–1904, the measured value of OIV*/OIV yields $n_e = 10^{3.9}$ cm^{-3}. Photoionization models yield the ionization parameter ξ, total column density N_H, and $n_e = 1.2 n_H$. Therefore, from the definition of ξ we obtain R ~ 700 pc. The top X-axis gives the distances for HE0238-1904, easily scalable for other objects.

At similar intermediate redshifts, X-ray diagnostic lines such as O VII and O VIII are absorbed by the local ISM, and X-ray fluxes are too low for spectroscopy. This makes studying the evolution of outflows difficult in the X-ray. In the UV at z<2, the integrated Lyα forest and continuum has an opacity of <10% (Zheng et al. 1997). An instrument with sensitivities of 100x COS would enable the detailed study of these UV species in hundreds of AGN. A UV spectrograph would be far more sensitive to outflows dominated by warm absorbers than any proposed future X-ray telescope, and with resolving power of 20,000, it would enable detailed kinematical studies as well. Again, the same sample of AGN used as background sources for probing the ISM, the IGM and the CGM would provide a sample enabling us to characterize the evolution of AGN outflows with redshift. This span of time covers the evolution of the cosmic star formation rate from its peak at z=2 until the present (e.g., Hopkins & Beacom 2006). Since outflows may be a key ingredient in regulating star formation and galaxy growth, understanding their co-evolution over the same time interval is crucial.

The Physics of the Accretion Disk Spectrum in the Extreme UV

AGN spectral energy distributions peak in the ultraviolet (Elvis et al. 1994; Telfer et al. 2002; Shang et al. 2011). While the bulk of this emission is likely the thermal emission from an optically thick accretion disk, the spectral shape in the extreme ultraviolet and how this connects to the soft X-ray is largely unknown due to absorption by the Milky Way ISM. At intermediate redshifts, portions of this band become directly visible. Temperatures producing a thermal peak at ~1200 Å (Telfer et al. 2002) are too cool for thermal radiation from the accretion disk to continue to the soft X-ray band (e.g., Done et al. 2012), and a likely explanation for the extreme ultraviolet continuum is Comptonization of the disk spectrum by a warm, ionized coronal layer just above the disk or near its inner edge, as shown in Fig. 3.

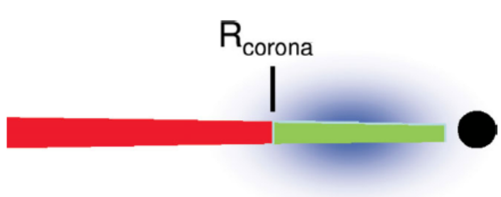
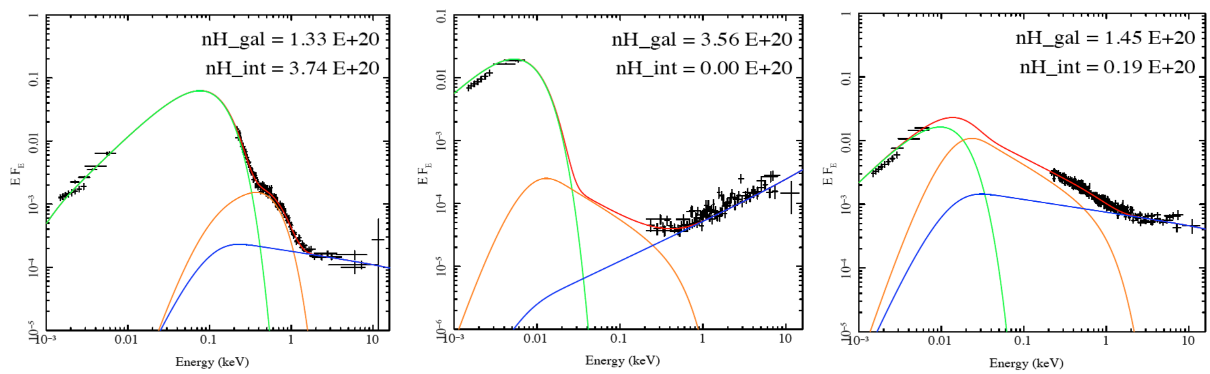


Figure 3: The thermally emitting outer disk is in red. In the inner disk (green) thermal photons are Compton scattered by "warm" gas to make the extreme ultraviolet/soft-X-ray excess. A hot inner corona (blue) Compton scatters the thermal radiation from the outer disk to produce the hard X-ray power law. (Adapted from Done et al. 2012.)

Jin et al. 2012 fit such a 3-component model to the SEDs of a sample of 51 low-z AGN with SDSS and XMM-Newton spectra. Fig. 4 shows striking variations in the contribution of the disk thermal component and the warm Comptonized contribution in the unobservable extreme UV. Observation of this portion of the spectrum in intermediate redshift AGN (z~1) will directly reveal objects with dominant thermal peaks (e.g., RBS 0769 in Fig. 4) and those with strong Comptonized tails (like PG1114+407). Existing ground-based observations (e.g., SDSS DR7, Shen et al. 2011) would give fundamental parameters such as M_{BH} and L_{Edd} to test the hypothesis that strong thermal peaks at short wavelengths are correlated with super-Eddington accretion, while strong Comptonized tails predominate in sub-critical disks. In objects with a strong Comptonization component (like PG1114+407 in Fig. 4), simultaneous optical observations would allow direct correlation of the soft seed photons from the disk with the Compton-scattered EUV. The high sensitivities we discuss below would allow high S/N observations on the short intraday timescales expected for radiative reprocessing in the disk. Lags in the correlation would then yield the geometry of the scattering region.

Figure 4: Three-component continuum fits to three example AGN from Jin et al. (2012). Left: RBS 0769 (L/L_{Edd}=13). Center: PG1004+130 (L/L_{Edd}=0.08). Right: PG1115+407 (L/L_{Edd}=0.4).



As in the prior two examples discussed above, the same sample of AGN used as background sources for probing the ISM, the IGM and the CGM would simultaneously provide the necessary targets for the scientific objectives described here.

Direct Black Hole Mass Measurements to Cosmological Distances

Understanding the influence of black holes on galaxy formation and evolution also requires knowledge of galaxy structures and black hole masses as a function of redshift. Direct dynamical measurement of black hole masses requires only modest spectral resolution but high spatial resolution. Angular scales of 0.01" resolve nuclear gas disks similar to that in M87 (Ford et al. 1994) under the influence of central black holes with $M_{BH} > 10^{9.3}$ $M_{\odot}$ at all redshifts (Batcheldor & Koekemoer 2009). Keplerian velocities of hundreds of km s^{-1} require resolving powers of only ~1000. Surface brightness dimming then becomes the limiting factor, requiring a corresponding increase in telescope aperture. Batcheldor & Koekemoer (2009) show that the resolution and low sky brightness afforded by the Lyα emission line in the UV is more efficient than 30-m ground-based telescopes in the IR. A disk with the Lyα surface brightness of M87 requires an 8-m space-based telescope to make the required observations to a limiting redshift of z=1.5 (see Fig. 5). Equipping such a telescope with an integral-field spectrograph with a field of view of ~1" and 4 mas pixels would achieve such measurements to a S/N of 5-10 in exposure times of 17—70 h.

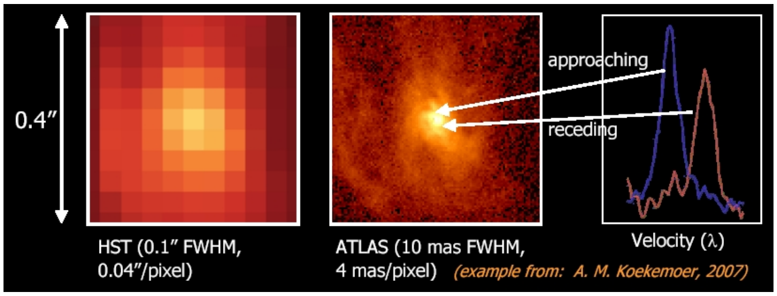


Figure 5: An example of a 250 pc radius nuclear disk (based on the M87 black hole, Ford et al. 1994), extrapolated to z~1.5 (where 250 pc subtends ~0.03"). (Left) Appearance of the disk with HST; (Middle) Appearance of the disk with a ~10 mas PSF (8-m space telescope, diffraction limited to 3000 Å); (Right) spectra in the central few hundred parsecs.

Observational Requirements for AGN Science

Spectral features in the absorption troughs of AGN outflows typically show component widths of 30—100 km s^{-1}. Resolving these in the lithium-like doublets to decompose the column density and covering fraction requires resolving powers of R~15,000. Measuring the column density and covering fraction in deep absorption troughs requires S/N=10 *in the bottom of the trough*. For typical troughs that are 10% of the continuum level, this implies S/N~30 in the continuum. COS can reach this S/N at flux levels of $F_\lambda > 6\times10^{-14}$ erg cm^{-2} s^{-1} $Å^{-1}$ in 1 orbit, or ~2000 s. This is equivalent to i=13.5 for a QSO with an SED matching the SDSS composite spectrum. However, only a handful of AGN are this bright, i.e., all the examples cited in the preceding sections. The scientific objectives described above require comprehensive surveys providing comparable spectra of hundreds of AGN. Short observing times not only enable large surveys, but also permit us to probe intraday variability. At i<17, and predicted $F_\lambda > 1\times10^{-15}$ erg cm^{-2} s^{-1} $Å^{-1}$, SDSS DR7 has over 250 AGN with $0.89 < z < 1.50$ (which enables us to see Mg X at λ>1150 Å and Lyα at λ<3200 Å). Observing these targets in 2000 s requires ~60x the throughput of COS. All requirements can be readily met with an 8-m UV/optical telescope with sensitivity down to the Lyman limit at 912 Å.

The lead submitter, Gerard Kriss, would be happy to present the science objectives described here at a NASA workshop.

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A Science Whitepaper submitted in response to the 2012 COR RFI for UV/Optical Science Investigations

Active Galactic Nuclei and their role in Galaxy Formation and Evolution

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Overview

Nuclear super-massive black holes (SMBH) seem to be a fundamental constituent of galaxies. Their growth as active galactic nuclei (AGN) produces a significant fraction of the luminosity in the universe. Moreover, the masses of galactic bulges and SMBHs appear to correlated, which suggests the importance of the AGN in galaxy evolution (e.g., via AGN feedback). However, we face a basic limitation. AGN have been the archetypical "point sources" for 50 years: no spatial structure has been resolved in the inner regions in which the winds and jets involved in feedback processes arise. Space-based UV/optical interferometry is the *only* technologically feasible means to probe these inner regions.

Scientific Background

AGN have been studied over the entire electromagnetic spectrum, using both ground-based and satellite observatories. The basic aspects of the phenomenon are generally agreed upon. As shown in Figure 1, the AGN can influence its host galaxy at scales ranging up to Mpcs. However, in order to fully probe the critical role of the AGN in galaxy formation/evolution, new capabilities are required: specifically, sub-milliarcsecond (sub-mas) optical/UV imaging that can only be achieved with space-based, long-baseline (0.5-1.0 km) observatories, e.g.,via an UV/optical interferometer (UVOI).

A fraction of galaxies harbor powerful non-stellar energy sources, AGN, at their gravitational centers. AGN emit radiation at all energies and span a huge range in luminosity, from Low Luminosity AGN and LINERs, to Seyfert galaxies, and, finally, QSOs. The source of the AGN's power is believed to be accretion of matter by an SMBH in the center of the host galaxy's nuclear bulge. Matter in the host galaxy, having lost angular momentum, spirals towards the SMBH, forming an accretion disk.

Viscous forces heat the disk to ~ several x 10^4 K. A hot (>10^6 K) coronal forms above the disk, most likely heated via magnetic reconnection, Thermal photons from the disk are up-scattered by relativistic electrons in the corona, producing EUV–X-ray continuum radiation. Also, relativistic particles are accelerated and collimated along magnetic fields in the inner parts of the disk and are ejected along the rotation axis of the SMBH/disk system, forming the extended jets observed in some AGN.

The optical and UV spectra of AGN are characterized by broad emission lines. Doppler-broadened permitted lines, with full width at half maximum (FWHM) > several 1000 km s^{-1} are thought to form in dense gas in a region within tens of light days from the central black hole, referred to as the “Broad Line Region (BLR)”, while forbidden lines, with FWHM< 1000 km s^{-1}, form in lower density gas in the “Narrow-Line Region (NLR)”, which may extend from 1 pc to several kpcs (depending on luminosity, see Bennert et al. 2002). Furthermore, AGN are divided into Type 1s, which show broad permitted lines and non-stellar optical continua and Type 2s, which have permitted and forbidden lines of similar widths and continua dominated by the host galaxy (Khachikian & Weedman 1974). The discovery of polarized broad lines in the spectra of Type 2 Seyfert galaxies (Miller & Antonucci 1983) led to the unified model which posits that the two types are intrinsically the same but that our line-of-sight to the BLR and accretion disk in Type 2s is blocked by a dusty circumnuclear torus (Antonucci 1993).

There are several key questions as to the nature and origin of AGN that can be addressed only by probing their central regions with sub-mas angular resolution at UV/optical wavelengths. These include 1) what initiates the active phase, 2) the duration of the active phase, and 3) the effect of the AGN on the host galaxy. Notably, from careful studies of the rotation curves of nearby galaxies, it is believed that all galaxies with massive bulges possess the “engine” of the AGN, i.e. a SMBH in their centers (Kormendy & Richstone 1995). Remarkably, the SMBH mass is roughly proportional to the galaxy bulge mass over more than 4 orders of magnitude (Ferrarese & Ford 2005): $M_{SMBH} \approx 0.002$ (±0.4 dex) x M_{bulge}.. For example, in a giant Elliptical galaxy in the present epoch, the SMBH may have accumulated up to $10^{10}\,M_\odot$ over a Hubble time.

This relationship suggests that the growth of the SMBH has kept pace with the process of hierarchical galaxy assembly (e.g., Cohen et al. 2006). The trigger for the build-up of the bulge/SMBH is thought to be major galaxy mergers, which, in turn feed the central accretion disk and initiate a burst of star formation. **The current paradigm posits that the accumulation of matter in the bulge is halted by the effect of the AGN, i.e. “AGN feedback'” (e.g. Kauffmann & Haehnelt 2000).** One can divide the AGN feedback into 1) radio-mode feedback, in which the onset of the jet disrupts gas cooling in the galaxy's halo (Croton et al. 2006), and 2) quasar-mode feedback, in which the powerful radiation emitted by the AGN drives material out of the galactic bulge (Hopkins et al. 2006). There appears to be a significant (1-2 Gyr) time delay between each merger and the ignition of the AGN (Hopkins et al. 2006), in part due to the time it takes material in the disk to reach the vicinity of the SMBH. Statistical studies suggest that the lifetimes of AGN are ~ several x10^7 yrs (e.g. Kauffmann & Haehnelt 2000), or roughly 1% of the typical major merger timescales. Hence, the bulge/SMBH is built-up via a number of major mergers, between which the AGN is in a quiescent state (during which there may be some low-level of activity).

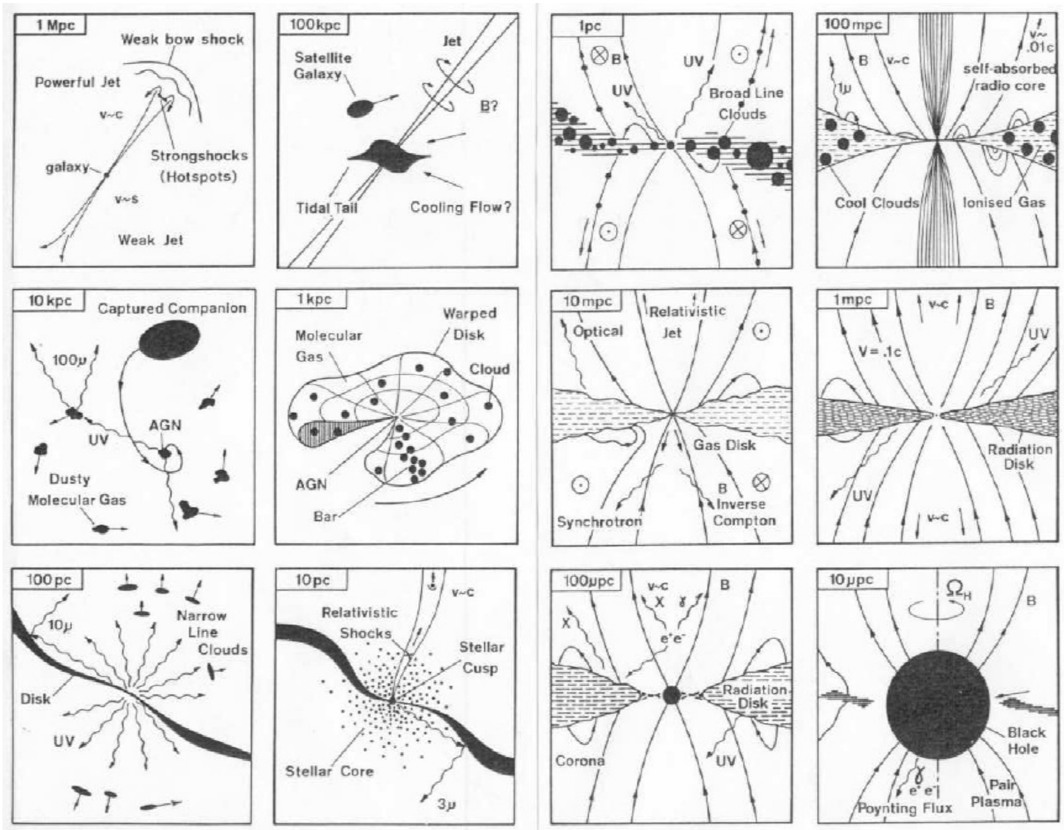

Fig.1 : Summary of how AGN affect their surroundings over 12 orders of magnitude in size: from relativistic radio jets at Mpc scales (upper left) to the supermassive black-hole (SMBH) and its surrounding accretion disk at AU or micro-pc scales (lower right). Starting from the upper left, each next panel is expanded by a factor of 10. The SMBH is well visible in the lower right two panels, and the inner accretion disk and torus in the right 6 panels (pc-AU scales). The outer AGN accretion disk and the escaping relativistic jet are well visible in the left 6 panels (Mpc-pc scales), with the galaxy itself shown in the 100-kpc panel (2nd from upper left). Figure from R. Blandford in Active Galactic Nuclei (1990; Springer Verlag, Berlin).

Approximately 50% of Type 1 AGN show blue-shifted absorption lines in their UV spectra (Crenshaw et al.1999; Ganguly & Brotherton 2008), indicative of mass outflow. In order to power the AGN, mass must be driven from the vicinity of the SMBH to remove angular momentum from the accretion disk (e.g., Blandford & Payne 1982). Hence, mass outflow is an essential element in the energetics of AGN (Elvis 2000). In Seyfert galaxies, the outflow appears to be driven by magneto-hydrodynamic processes (e.g., Kraemer et al. 2005; Turner et al. 2005), while the more energetic outflows detected in QSOs are more likely radiatively driven (e.g., Arav et al. 1995). For Seyferts, and other low-luminosity AGN, the mass loss rates and kinetic luminosities are much lower than required for AGN feedback. However, QSOs show much more energetic, and optically thick, outflows (e.g. BAL QSOs). In fact, outflow velocities of several x 10^4 km s^{-1} have been detected (e.g. Ganguly & Brotherton 2008). Hence, the QSO outflows share the characteristics of the initial AGN turn-on that is thought to have occurred during the bulge formation.

For the most part, what has been learned about mass outflow has come from absorption-line studies. From these, the column densities, radial velocities, and, in some cases, radial distances for the absorbers have been determined (e.g. Arav et al. 2008). However, in order to determine mass-loss rates and kinetic luminosities, one must determine the total amount of material in the outflow, specifically the global covering factors of the absorbers. One way to determine the covering factors is by spectral imaging of the outflowing gas. Using HST/STIS long slit spectra, Crenshaw & Kraemer (2007) were able to identify in emission one component of the outflow in the Seyfert 1 galaxy NGC 4151, but only were able to resolve structure of ~10 pc in extent, while the bulk of the outflow is ~ 0.1 pc from the AGN. However, with 0.1 mas resolution achievable via UVOI, we can resolve the inner 10 light days in local AGN such as NGC 4151. This is just outside the BLR region (Clavel et al. 1990), and, since the absorbers appear to cover the BLR emission (Crenshaw et al. 1999), this allows us to probe the region in which the bulk of the outflowing mass exists. More importantly, scaling up to redshifts of $z \sim 0.5$, we will be able to resolve structure of ~ 1 pc. Hence, we will be able to map the global extent of the outflows in intermediate redshift QSOs, thereby obtaining accurate constraints on their energetics.

Based on the strong UV resonance lines that are the main signatures of mass outflow, the best way to map their global extent is via Ly-α and C IVλ1550. Although these lines dominate the BLR spectra of AGN, with UVOI resolution we will be able to remove the unresolved BLR and directly detect the Ly-α and C IV from the surrounding gas.

Scientific Goals

To summarize, the main science goals that can be achieved with UVOI interferometry are as follows:

1. Constraining the dynamics of AGN feedback. As noted above, UVOI spectral imaging will be used to map the outflows in intermediate redshift QSOs. This will provide new insight into AGN feedback with which models of hierarchical build-up of galactic bulges can be tested.

2. Probing the BLR/NLR transition regions in AGN. Based on high-resolution UV spectroscopy, the bulk of the absorbing material in AGN lies outside the BLR, most likely in the BLR/NLR transition region. Resolving this zone will allow us to trace the launch point of the mass outflow. This will give us new insight into how gas is ejected from AGN.

3. New insights regarding the structure of the torus. One possible source for the outflow is ablation of material from the inner face of the torus. Note, that sub-mas resolution will allow us to probe the sublimation regions over a fairly large range in redshift, which is relevant to both the torus structure and the BLR/NLR transition region.

4. Jet formation/collimation. Although we will not have the ability to trace the jet back to the accretion disk, this is also the region where the relativistic jet is collimated for its journey of over 7 orders of magnitude in distance into the intergalactic medium. Furthermore, the UV/optical spectral images will be complementary to the ground-based VLBI and IR observations.

5. Precise measurement of the average opening angle of AGN at sub-pc scales. With a UVOI we can obtain a direct measure of the average cone opening angle of AGN, and if this number is close to 45° this would be a strong direct confirmation of the AGN unification picture. If significantly different from 45°, then the AGN unification picture may well be incorrect, posing a severe challenge to the field.

Future Directions

An additional science goal of an UVOI will be standard-length distance measurements. Mapping the 3-D geometry of the Universe involves measurement of the large "cosmic" scale distances of high redshift sources such as distant supernovae and quasars. Standard distance measurements use relative distance estimation, e.g., the brightness of supernovae of type SNIa at z ~1.5 as “standard candles” (Perlmutter et al. 1999). Recently Elvis & Karovska (2002) proposed an absolute method for estimating distances to quasars at different redshifts using long-baseline interferometry of quasar BLRs, which would provide an independent check on the standard technique. This geometric method uses the size of the quasar BLR from reverberation mapping (Peterson et al. 2004) combined with interferometric measurements of the angular diameter of the emitting region to derive the distance to the quasar. The quasar broad emission lines (v~5000 – 10,000 km s^{-1}) originating in the BLR gas clouds respond to changes in the continuum source in the center by changing their intensity (~20% in the UV) with a time-lag of a few days to years. This time-lag is induced by the light travel time from the continuum source. For low redshift quasars the size of the BLRs is ~10 light days corresponding to an angular size of a fraction of a mas (Figure 2). When compared to relative distance estimators this method is much less dependent on physical models and on changes in the fundamental constants (other than c, the speed of light) because it uses a standard-length measurement approach rather than a standard-candle approximation. Although there are currently a small number of AGN with BLRs that can be resolved with 0.1 mas imaging, extending by another factor $10\text{-}10^3$ in spatial resolution, which will not only resolve the BLR, but will allow us to reach the Schwarzschild radius of $10^8\text{-}10^9\,M_{sun}$ SMBH's. These will conceivably yield the first direct measures of black-hole shadows.

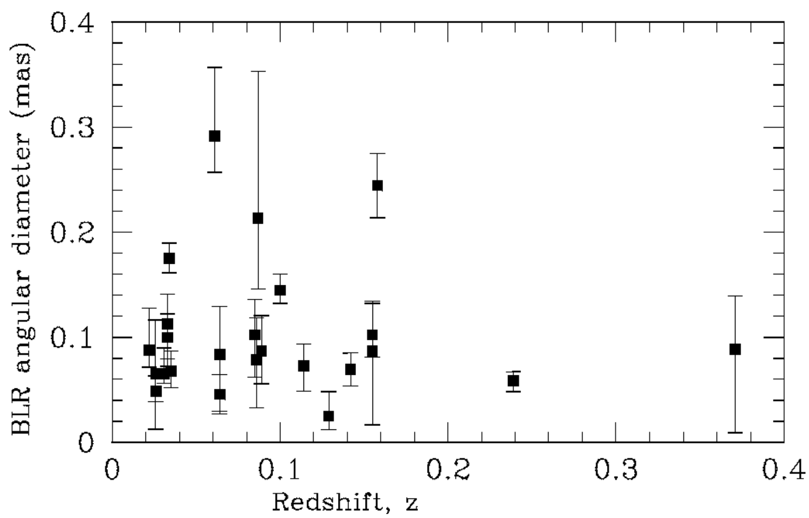

Figure 2: Angular diameters for the Hα and Hβ BELRs of nearby active galaxies, assuming H_0=65 km $s^{-1}Mpc^{-1}$. (Peterson et al. 2004, Kaspi et al. 2000)

Summary

We have presented the compelling new AGN science that can be accomplished with sub-mas resolution. In particular, such observations would enable us to constrain the energetics of the AGN “feedback” mechanism, which is critical for understanding the role of AGN in galaxy formation and evolution. These observations can only be obtained by long-baseline interferometers or sparse aperture telescopes in space, since the aperture diameters required are in excess of 500 m – a regime in which monolithic or segmented designs are not and will not be feasible and because these observations require the detection of faint emission near the bright unresolved continuum source, which is impossible from the ground, even with adaptive optics.

Relevance to Top-Level COR Science Objectives

The science investigations described herein contribute to investigations of several of the high-level COR science objectives, including: "how are the chemical elements distributed in galaxies and dispersed in the circumgalactic and intergalactic medium?" and "when did supermassive black holes form in the early Universe, and how have they affected the evolution of the galaxies in which they are found?" This whitepaper also responds to the RFI request that respondents "attempt to imagine compelling scientific investigations in an era well beyond the present" to support the synthesis of a "wide range of far-reaching ideas", goals readily met by investigations requiring the ultra-high angular resolution described in this whitepaper.

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UV Spectroscopic Time Domain Studies of Active Galactic Nuclei

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Overall Goals:

Time domain spectroscopic studies of active galactic nuclei (AGNs) enables:

1) Determination of the structure and kinematics of the gaseous regions in the immediate vicinity of the central supermassive black holes, thereby clarifying the role of this gas in both fueling (inflow) and feedback (outflows).
2) Accurate measurement of the masses of the central black holes.
3) Measurement of luminosity distances to high-redshift quasars and determination of cosmological parameters to high redshift, independent of any other method.

Introduction:

"Reverberation mapping" (Blandford & McKee 1982; Peterson 1993) is a spectroscopic time-domain technique that can be used to determine the structure and dynamics of the broad-line region (BLR) of AGNs. Reverberation mapping can provide us (a) with insights into mass outflows and mass accretion on microarcsecond scales, too small to be resolved by any other direct method, and (b) a means to directly measure the masses of the central black holes in these objects. Moreover, secondary methods anchored by reverberation mapping results allow us to estimate masses in active nuclei to arbitrarily large cosmic distances, addressing the Cosmic Origins goals of determining when supermassive black holes form and how have they affected the evolution of galaxies in which they are found. Indeed, all black hole mass estimates beyond the local universe are based on scaling relationships anchored by reverberation. In addition, the luminosities of AGNs can be inferred by BLR sizes determined by reverberation mapping, providing a direct measure of luminosity distances to quasars and allowing determination of cosmological parameters at redshifts as high as $z = 3$ or more (Watson et al. 2011).

Background:

Supermassive black holes reside at the centers of most, if not all, massive galaxies. Some 5–10% of these black holes are actively accreting mass at a high enough rate to form a radiatively efficient accretion disk. On spatial scales of a several to a hundred gravitational radii ($R_g = GM/c^2$), the accretion disk emits thermal radiation across the electromagnetic spectrum. On scales of a few hundred to thousands of gravitational radii, nebular gas is ionized by radiation from the accretion disk and reprocesses the incident radiation into emission lines that are Doppler broadened to thousands of kilometers per second by the rapid motion of the gas in the deep gravitational potential of the black hole (hence the name "broad-line region"). The radiation from the accretion disk varies irregularly with time and the emission lines respond to these variations, but with a time delay due to the light-travel time across the BLR. Measurement of these time delays, or "lags," is the core of the reverberation mapping technique. The emission-line lag τ is the mean light travel time across the BLR radius $R = c\tau$.

Scientific Results from Reverberation Mapping:

Measurement of emission-line lags has yielded two very important results:

1) By comparing lags and line widths for multiple emission lines in an AGN, we find an inverse relationship between line width ΔV and lag τ that is consistent with the virial prediction $\Delta V \propto R^{-1/2}$ where $R=c\tau$. This means that, up to a projection factor that must be calibrated locally, the product $\Delta V^2 R/G$ yields the mass of the central black hole (Peterson & Wandel 1999, 2000, Kollatschny 2003; Bentz et al. 2009b). Higher ionization lines are broader and have shorter lags than low-ionization lines, demonstrating the ionization stratification of the BLR (Clavel et al. 1991).
2) The size of the BLR as measured for a particular emission line is closely related to the luminosity of the AGN in the approximate form $R \propto L^{1/2}$ (Kaspi et al. 2000, 2005; Bentz et al. 2006, 2009a). This radius–luminosity (or "R–L") relationship is at the present time well-established only for Hβ (Figure 1).

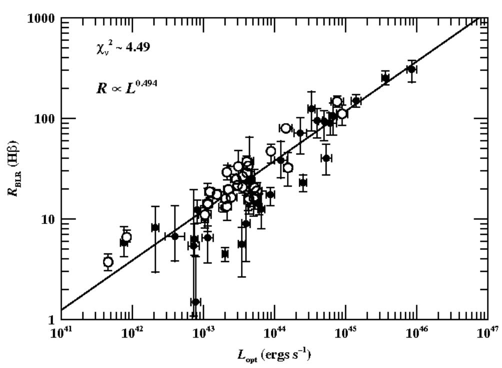

Figure 1. The relationship between starlight corrected optical luminosity and broad-line region radius as measured for the Hβ emission line. The open symbols represent the highest-quality reverberation measurements. Based on Bentz et al. (2009a).

In addition to the implications for photoionization physics, the *R*–*L* relationship is particularly important because it affords a viable short-cut to estimating AGN black hole masses (Wandel, Peterson, & Malkan 1999), although at the present time these are accurate to only a factor of three or so and possible systematics, such as the possible (probably minor) role of radiation pressure (Marconi et al. 2008), are still under investigation. From a single spectrum, we can measure the luminosity (and thus infer the BLR size *R*) and combine this with the emission-line width ΔV to estimate the black hole mass.

Another potentially important application of the BLR radius–luminosity relationship has emerged recently, namely as a “standard candle” for cosmological investigations. We can use reverberation mapping to measure the BLR size in distant quasars and then infer the intrinsic AGN luminosity from the *R*–*L* relationship. By comparing this with the measured AGN flux, we infer the luminosity distance D_L (Watson et al. 2011). Reverberation mapping of quasars at high redshift will allow us to probe the equation of state of the universe at redshifts $2 < z < 3$, beyond the reach of supernovae, and will provide an important cross-check on the results from measuring the baryon acoustic oscillations scale at these redshifts using QSO absorption lines.

Velocity–Delay Maps:

Beyond the measurement of a mean time delay for each emission line, transformational developments are possible by improving the delay resolution through high-cadence monitoring sufficient to support high-fidelity velocity-delay mapping. With enough high-quality data, it is possible to resolve the time-delayed emission-line response to continuum changes as a function of Doppler velocity and obtain a “velocity-delay map” (Figure 2). Velocity-delay maps can then be modeled to determine the geometry and kinematics of the broad-line region (Horne et al. 2004; Pancoast, Brewer, & Treu 2011). The emission-line variations, as a function of time *t* and Doppler velocity *V* can be written as

$$L(V,t) = \int_{-\infty}^{+\infty} \Psi(V,\tau)\ C(t-\tau)\ d\tau,$$

where $C(t)$ is the continuum light curve, τ is the time delay, and $\Psi(V,\tau)$ is the velocity-delay map. It is apparent by inspection that $\Psi(V,\tau)$ is the observed emission-line response to a delta function continuum outburst. The goal of a reverberation experiment is to recover the velocity-delay map from the observables, i.e., the continuum $C(t)$ and velocity-resolved emission-line $L(V,\tau)$ light curves. By obtaining velocity-delay maps for multiple broad emission lines spanning a range in ionization level and hence distance from the central source, we can model the structure and kinematics of the BLR gas.

There are multiple lines of evidence, supported by current reverberation studies, that the BLR is a manifestation of the inflow and outflow processes in AGNs. In principle, recovery of velocity-delay maps for different emission lines allows us to determine in detail the structure of the gas flow because the different ionization potentials mean that the different lines probe regions at different distances from the black hole. In particular, the low-ionization lines are thought to arise principally in a disk-like inflow that may be an extension of the accretion disk structure, while the higher-ionization lines may have a component that arises in an outflowing wind. The observed ionization stratification of the BLR means that the mostly optical low-ionization lines arise in the outer BLR while the mostly UV high-ionization lines arise in the inner BLR. Both optical and UV velocity-delay maps are necessary for a complete picture of the BLR structure and kinematics.

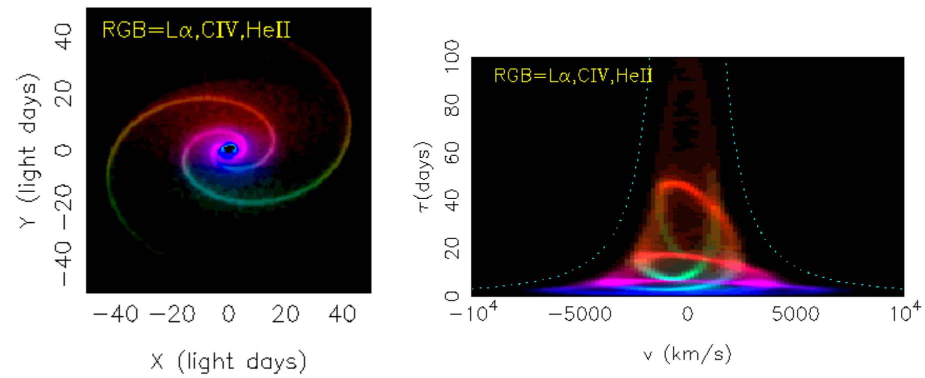

Figure 2: A photoionization model of a hypothetical BLR as a two-armed spiral disk is shown on the left, with red representing Lyα emission, green C IV λ1549 emission, and blue He II λ1640 emission. The panel on the right shows this disk transformed into a velocity-delay map. The structure of the disk is entirely arbitrary, but the velocity-delay map shows clearly how multiple emission lines are required to see the full structure of the BLR. From Horne et al. (2004).

Current Limitations:

The rest-frame ultraviolet is the most important part of the spectrum for reverberation mapping of AGNs. The strong C IV λ1549 line, in particular, which is expected to show a strong outflow signature, is in this part of the spectrum, as are other important emission lines, He II λ1640, N V λ1240, and Lyα λ1215, which are all known to have relatively short reverberation time scales. Also, the observable UV continuum (~1350Å) is expected to be a much better proxy than the optical continuum (~5100Å) for the hydrogen-ionizing continuum shortward of 912Å that actually drives the emission lines; indeed the UV and extreme UV are known to be highly correlated (Marshall et al. 1997).

Unfortunately, very few UV spectroscopic time series for reverberation mapping exist, and these are mostly for nearby low-luminosity AGNs that were observed with the *International Ultraviolet Explorer* prior to its termination in 1996.

The situation with velocity-delay maps is, of course, even poorer. Intensive ground-based optical campaigns have begun to yield credible velocity-delay maps (Bentz et al. 2010; Denney et al. 2011; Grier et al., in preparation), but UV velocity-delay maps (e.g., Ulrich et al. 1996; Wanders et al. 1997) give only hints of the structure of the high-ionization BLR. Despite the difficulties involved[1], optical ground-based reverberation mapping of

[1] Reverberation mapping at high redshift presents additional challenges: (1) Timescales are expanded by time dilation, requiring spectroscopic monitoring programs longer by a factor of (1 + z) compared to local AGNs of the same luminosity. (2) The reverberation timescales are longer for the more easily monitored high luminosity sources as their BLRs are larger. Moreover, compared to lower luminosity AGNs, the amplitude of continuum variability is lower in high luminosity objects and the continuum signal is

the rest-frame UV in high-redshift AGNs will be needed for a cosmology program. But UV reverberation mapping of relatively local AGNs is a critical first step in order to establish the radius-luminosity relationship for C IV over a large range of luminosity. Moreover, reverberation mapping of C IV in local sources is required to effect a direct comparison of black hole mass measurements based on Hβ with those based on C IV. The inescapable conclusion is that UV observations are required to meet any of the science goals described below.

Proposed Science Programs:
There are three distinct reverberation mapping programs that should be carried out:

1) Intensive monitoring campaigns to obtain high-fidelity velocity-delay maps for high ionization lines in the UV. The main scientific goal of this program is to obtain velocity-delay maps of the high-ionization lines to determine the structure and kinematics of the high-ionization BLR. To get a sense of the requirements, bright local Seyfert 1 galaxies might require 1–2 observations per day for up to 6–8 months (Horne et al. 2004). The cadence translates directly into the spatial resolution of the BLR. The necessary duration of a monitoring campaign should scale with BLR size ($\tau = R/c \propto L^{1/2}$).
2) Moderately high cadence UV spectroscopic monitoring campaigns of low-redshift AGNs over a broad range of luminosity. The goal of this scientific program is to establish the BLR radius–luminosity relationship for the C IV emission line as this will be essential for (a) estimating quasar black hole masses at larger redshifts and (b) enabling cosmological applications.
3) Moderately high cadence UV spectroscopic monitoring campaigns of AGNs at redshifts up to about 1.5 in order to use the C IV BLR radius–luminosity relationship to establish luminosity distances and thus measure cosmological parameters. Quasars at larger redshifts can be studied from the ground.

Requirements:
The technical requirements for reverberation mapping are fairly modest, with the most important attribute being the ability to obtain spectra with a relative flux calibration that is accurate at the 1% level. This requirement primarily impacts pointing stability. A two-meter class telescope (or even smaller for some of the more local applications) and a spectrograph with resolution $R > 600$ (higher is better) covering the spectral range 1100 – 3000 Å (or a long wavelength cutoff ~2000 Å to execute only the first two proposed programs) would be sufficient to meet the science goals outlined here, though a larger aperture would decrease exposure time and/or increase the number of sources that could be observed.

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geometrically more diluted over the larger BLR, making the line variations smaller and harder to measure accurately. (3) Reverberation observations of high-redshift AGNs of luminosity comparable to those studied locally will require large time allocations on very large telescopes.

Summary:
Reverberation mapping is an indirect imaging method that assembles the time-resolved spectroscopic data into a two-dimensional velocity-delay map of emission line regions photoionized by the accreting black hole. Just as radio interferometry lets us “see” the jets and radio lobes generated by AGNs, velocity-delay maps sharpen our view of AGN emission-line regions, delivering microarcsecond resolution, with revolutionary potential for our understanding of these enigmatic objects.

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In response to Request for Information NNH12ZDA008L: ***Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts***

EXTRAGALACTIC LYMAN-ALPHA EXPERIMENTS IN THE NEARBY UNIVERSE

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Abstract. The universe has been statistically studied in the HI Lyman-alpha emission line only at redshifts (z) above 2. Thus despite living in a universe where Lyα is the brightest spectral feature of the most abundant species of baryonic matter, 75 per cent of our cosmic history is left unexplored. Here we outline the scientific case and approximate requirements for a space-based UV facility that could efficiently cover the remainder. Lyα is the most important spectral beacon in high-z astrophysics, where studies of galaxy formation, the cosmic web, and the epoch of reionization all rely upon Lyα population statistics. The unbiased assembly and study of a large sample of Lyα-galaxies at low and moderate redshifts is the only method through which we can truly rely upon Lyα as cosmological diagnostic tool. Simultaneously such observations would enable unprecedented studies of galaxy evolution and massive star formation across the latter 3/4 of cosmic time. A new UV-optimized mission with spectroscopic ($R \sim 10,000$) and spectrophotometric capabilities at $\lambda = 1200-3500$Å is the only way that these goals can be realized. We therefore strongly recommend the inclusion of these capabilities in a future facilities, and we are willing and able to contribute more detailed goals, requirements, and specifications and realistic simulations.

Authors are keen to participate in the workshop in Baltimore

1. Lyman-alpha Astrophysics and its Application

The HI Lyman-alpha emission line (Lyα) is the de facto spectroscopic feature of evolving galaxies in the high-redshift universe [1]. Reprocessing roughly 40 per cent of the intrinsic ionizing energy ($h\nu > 1$ Ryd) into a single high-contrast feature, Lyα surveys are able to probe the most abundant populations of faint, low-mass galaxies [2]. Simultaneously, and at luminosities 4 orders of magnitude brighter, Lyα-selection also recovers the most energetic systems in the known universe [3]. Because of the high survey efficiency of Lyα, such catalogues have been used for any number of studies of cosmic star-formation and galaxy clustering [4, 5, 6].

Lyα also occupies a prestigious place among observables from high-z galaxies, because it encodes further information that is unique and exclusive to the $n = 2 \rightarrow 1$ transition. Specifically Lyα also enables: studies of cosmic reionization [7], estimates of kinematic and gaseous properties of the ISM [8], a test of population III star-formation [9], a probe of the cosmic web [10, 11], and a diagnostic of circumgalactic gas via its polarization [12]. This is an impressive toolkit for a single monochromatic feature, and does not even mention the enormous impact of Lyα absorption studies.

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The convenient rest-wavelength of 1216 Å means that in principle all of the above studies may be executed, using identical methods, across the entire epoch of galaxy formation and assembly: $z = 2$ to 10 [13], and in principle up to ~ 20. This power of Lyα has motivated new generations of instrumentation for 8–10 m ground-based telescopes: Subaru/HyperSuprimeCam, VLT/MUSE[14], and the HETDEX[15]. Combined with very high-z science goals laid out for ELTs and JWST (specifically NIRISS), *the future of Lyα-related astrophysics is secured for the coming decades.*

This puts us in a situation that is very bright but, for two main reasons is also very unsatisfactory. Firstly Lyα is a resonance line and undergoes a complicated radiative transfer through the ISM. Indeed this is the very origin of some of the Lyα-specific science cases listed above, but also implies that the general use of Lyα photometry for cosmological purposes is severely biased. At this point, it is worth remembering that in high-z science, every calibration that relates an observable to a physical property has been derived in studies of nearby galaxies. At high-z the information required to empirically study radiative transport is completely ruled out by the large physical sampling scales, the lack of photons, and the redshifting of critical spectral features to the mid IR: detailed studies can only be performed in nearby galaxies. The second unsatisfactory element of Lyα astrophysics is that the universe at $z \lesssim 2$ is almost completely unexplored, at least statistically. This not only comprises 75% of cosmic history, but it includes the peak in cosmic star-formation, the emergence of the dominant Hubble sequence, dense galaxy clusters, and so on; the transition to the modern universe remains poorly studied in the UV.

2. Lyman-alpha Astrophysics and Low-redshift Observations

Early searches for $z > 3$ Lyα emitters (LAEs) found only their absence[16], although at that point it was not clear why the Lyα universe seemed so dark. Concurrently, observations of nearby starburst galaxies with the IUE were also finding a lack of strong Lyα emission [17, 18] although here the situation was clear: Lyα photons were being produced (shown by their strong Hα), but their emission heavily suppressed. This immediately raises the questions of *why?* and *what are the high-z implications?*

Regarding *why*, Lyα has a very high absorption cross section with dust, so the dust content must be a factor. However the chance of this absorption depends on the path the radiation takes, and thus for a resonant photon H I also enters in the most fundamental way. The geometry of galaxies is such that dust and H I give rise to an intricate and highly complex transport problem in which Lyα emission is regulated by dust [19] and its distribution [20], metallicity [21], H I content and kinematics [22], covering fraction [23], filling factor, and clumping [24]. See Fig. 1. Most of these properties are impossible to measure in high-z galaxies directly, and the bulk of the dependencies have been shown in small samples of nearby galaxies observed with IUE, HST, or GALEX, or have not been rigorously tested at all. Furthermore, the only current Lyα imaging program of nearby galaxies failed to find any correlations with dust on small scales, but did show Lyα scattering haloes that are significantly extended beyond Hα and the UV continuum, and clearly illustrated the difficulty of deriving aperture-integrated global quantities at both high- and low-z [25].

Two approaches lead low-z Lyα science: the *targeting of known galaxies* at $z \lesssim 0.1$ with HST, and *blind surveying for LAEs* at $\langle z \rangle = 0.3$ with GALEX grism spectroscopy. At $z < 0.1$ we are able to study galaxies in exquisite detail, and place constraints on many of the quantities known to govern Lyα transmission. Importantly, current radio facilities at

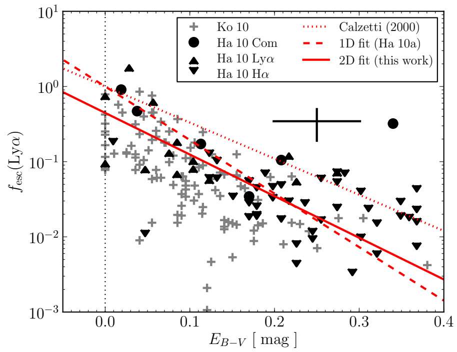

Figure 1. A comparison between the Lyα escape fraction and dust content of individual galaxies at $z = 2-3$ [13]. Clearly there is an anti-correlation between the two quantities, but the spread exceeds 1 dex (note the logged ordinate axis). This spread will likely be the combined effect of (some/all of) the many other quantities discussed in Section 2. Understanding why requires large, and unbiased samples of *nearby* galaxies.

21 cm give us direct access to the HI gas. Our own HST program, *LARS – the Lyman-alpha Reference Sample* (Fig. 2), has obtained Lyα, UV, and optical imaging and UV spectroscopy for 14 nearby starbursts with precisely this motivation. HST, however, was not optimized for this kind of science and, costing six orbits per target, extending LARS by the factor of ten to the $\gtrsim 100$ targets required for statistical coverage over the parameter manifold would require a *SuperLarge* HST program. Plausible, but better served with a new UV facility.

Lyα-selection with GALEX can reach statistical significance, and enables similar galaxy selection to that employed at $z > 2$. This is vital to examine the evolution of the luminosity function (LF)[26], the escape fraction [13], and prevalence fraction [27], and provide *the only datapoint in the last 75% of cosmic time* (Fig. 3). However with a 50 cm mirror GALEX is restricted to bright galaxies and unable to (a) probe the faint end of the LF (the critical part for reionization) and (b) find many $z \gtrsim 0.4$ objects (NUV spectroscopy at $\langle z \rangle = 0.9$ has found fewer than 10 galaxies [28]). Furthermore with the FUV channel of GALEX centering on Lyα emission at $z \sim 0.3$, spatial sampling and photon-statistics are reduced substantially compared to the very nearby universe, and indeed these galaxies are too faint to make HI detections or study the kinematics of the neutral gas, even with HST.

3. Lyman-alpha Experiments in the Nearby Universe

Our objective to be attained with the future UV telescope is to unambiguously determine the restframe UV and Lyα properties of the galaxy population that are a relevant for high-z astrophysics, and to do so at a redshift that makes the population amenable to detailed physical studies: $z \lesssim 2$. In tracing star-forming regions across the latter 3/4 of the universe, this will have direct application in galaxy evolution, and will provide synthesis information for very high-z galaxy and reionization studies provided by JWST and ELTs, and for computational models of galaxy formation.

Specifically for Lyα, to $z \lesssim 2$ this would include **blind surveys using both Lyα- and UV continuum-selection**. Driven by the increase in survey depths compared to GALEX and HST, we would measure the LF (including the faint-end slope), Lyα-fraction among UV galaxies (and other selection, e.g. Hα), global Lyα escape fraction, and EW distribution. In a sample of ~ 1000 objects (10-fold increase over today) we would track the evolution of these properties at statistically significant levels in several bins across the latter half of cosmic history. Working at $z < 2$, and down to $z \sim 0.2$, we would not only be able to say how the galaxies evolved, but would obtain all the information necessary to say why, and what physical processes shape the distributions. We would address a number of specific outstanding issues such as the disappearance of Lyα blobs, and the blind survey and comparison of Lyα with ionizing (Lyman continuum) radiation – see the responses

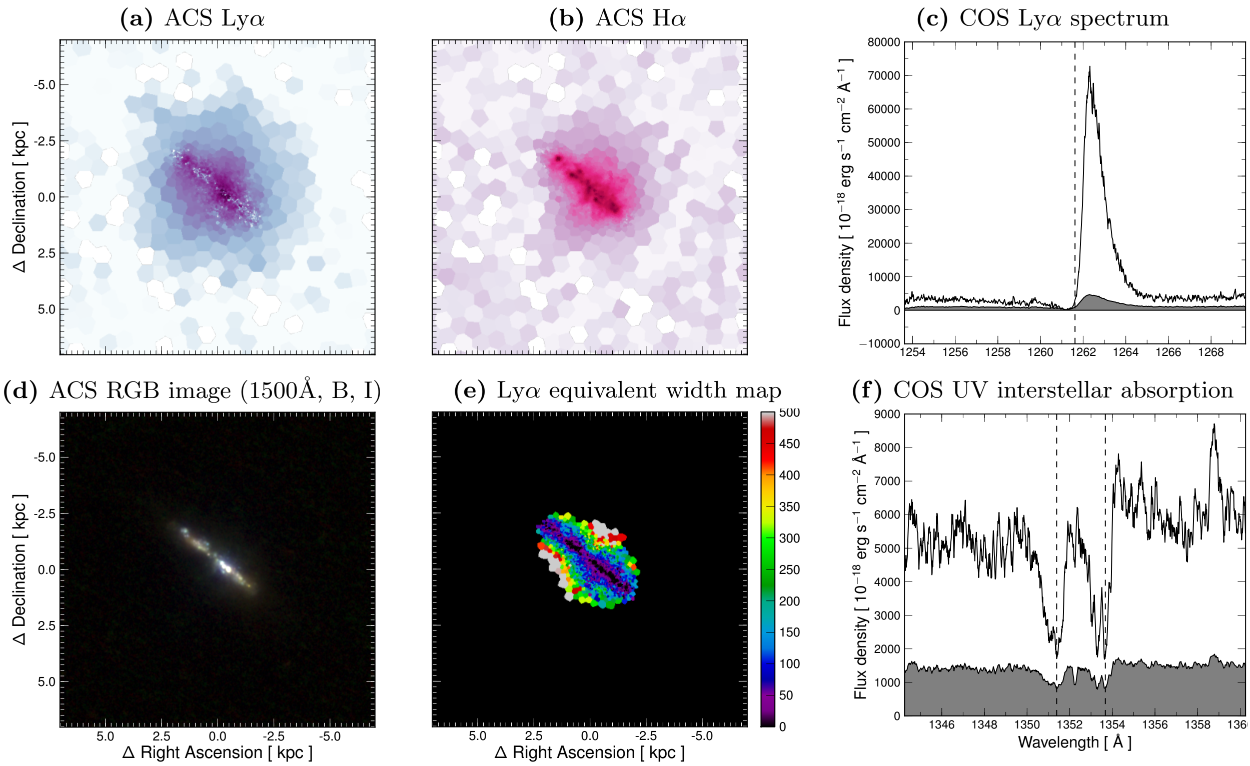

Figure 2. Results from the LARS program for Mrk 1486. Emission lines are continuum-subtracted and images are Voronoi binned for reliable surface photometry at faint isophotal levels. Lyα and Hα photons originate in the same nebulae, but Lyα clearly extends way beyond the nebulae in which it formed. This is most likely the result of scattering of photons by HI, and may also be seen in the equivalent with map: in the central regions the EW is low ($\lesssim 10$Å) as Lyα photons scatter out of the line of sight, but increases dramatically with projected distance from disk to values in excess of 500Å, as photons are scatter forming a diffuse halo. For reference, the intrinsic EW for star formation at equilibrium is 80Å. The spectra from HST/COS show a smooth and asymmetric (P Cyg-like) emission profile for Lyα and ISM absorption features (OIλ1302, SiIIλ1304) that are blue-shifted from their expected velocities. Both of these phenomena are consistent with Lyα being transmitted through out-flowing neutral gas, but note also the significant residual intensity in the core of the absorption lines, which suggests a covering fraction below unity.

to this RFI by C. Scarlata and S. McCandliss. This physical completeness would come through observations surveying for, and specifically targeting the Balmer series, oxygen, nitrogen and sulphur lines, and direct and indirect HI measurements. Naturally this implies synergies with ground-based telescopes including ELTs, space-based NIR platforms such as EUCLID/WFIRST and JWST, and radio facilities, (ALMA, possibly including the SKA).

For a complete picture, **detailed observations in the UV** are necessary. Spectroscopy would provide the only unambiguous tracers of the kinematics of the neutral ISM, gas covering fractions, and diagnostics of the massive stellar population. All of these have direct impact on Lyα, which remain to be studied at high statistical levels at any redshift, but all are also of immediate interest in their own right given that there are no evolutionary studies of any of them. Thus intermediate resolution UV spectroscopy would be necessary.

As shown by the LF, it is invariably the case that most of the objects found by a survey are faint. This usually restricts detailed followup studies to smaller subsets of the overall population: systematic and complete followup is performed at magnitudes where it is efficient, and successively more piecemeal, biased, or "ambitious" followup is attempted for the fainter systems. However the entire philosophy of analogue studies mitigates this issue and, by carrying the capability to observe down to Lyα in the restframe, one could also target

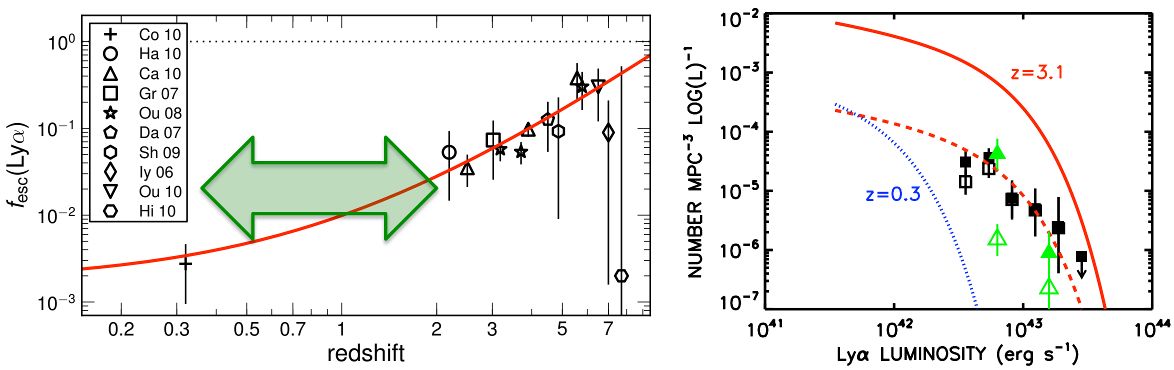

Figure 3. *Left*: Evolution of the Lyα escape fraction [13], which shows a clear and monotonic upwards evolution from the nearby universe to $z \sim 6$, after which point it reverses and the decreases. This shows the power of Lyα in probing the evolution of the galaxy population and also, most likely, the epoch of reionization. The green arrow shows the gap between $z \sim 0.4$ and 2.2, which constitutes > 7 Gyr of evolution. The point at $z = 0.3$ is derived from the blue LF in the *right* panel [28], which also shows the well-constrained LF at $z = 3$ (red). Note the enormous change, which evolves even faster than the declining cosmic star formation. The black points show limited constraints available from GALEX/NUV at $z \sim 1$, which include just 8 star-forming galaxies. The main goal of the program presented here is to find and understand ~ 1000 galaxies in this redshift interval, when the evolution in both cosmic star-formation and Lyα emission is strongest, yet galaxies are still near enough for detailed followup.

very faint galaxies by concentrating on the very nearest systems. Contrasting $z = 0.5$ with $z = 0.01$, the luminosity distance decreases by a factor of 60, sampling scale by a factor of 30, and surface brightness dimming by a factor of 4. Thus detailed observations could be performed down to the faintest limits of the galaxy LF probed in the high-volume surveys, if the telescope carries **capabilities down to ∼1216Å**.

4. Basic Technical Requirements

To give a rough feeling for the kind of hardware these studies would need, we transcribe them into the approximate telescopic capabilities that would fulfill our scientific goals.

Wavelength Coverage. Our recommended survey capabilities are driven by the need to cover redshifts from where the angular scale permits efficient surveying ($z \sim 0.2$) to the atmospheric transmission ($U-$band, at $z \sim 2$). This corresponds to $\lambda = 1500 - 3500$Å for a spectrophotometer. For high-resolution instruments we would need coverage down to 1200Å.

Observing Modes. Surveys can be accomplished in either slitless spectroscopic mode or imaging with narrowband filters (or pseudo-narrowband filters synthesized from long-pass filters [29]). A $R \sim 100$ slitless spectrograph would be more straightforward, especially in the low background of the UV, but a set of redshift-appropriate narrow and broadband filter combinations would also provide excellent spectrophotometry, morphological information, and reduce contamination. Wide field imaging (1500–3000Å) should also be explored.

An intermediate-resolution spectrograph is essential for any detailed studies (kinematics, stellar populations, covering fractions) and the medium gratings of STIS and COS ($R \gtrsim 10,000$) are ideal. The most important gain over current facilities would come from multiplexing capabilities, where configurable slits, micro-shutter arrays (E.g. JWST/NIRSpec), or integral field capabilities would be revolutionary in the UV. Wavelength coverage should at least match the spectrophotometer; to 1200 Å would be preferred.

For thorough work at $z < 0.1$ an imager is vital. Spectroscopic apertures almost never capture diffuse Lyα components that can dominate the total output[25, 23]. Also it is only at $z \lesssim 0.1$ that scales < 100 pc can be explored. HST can image at 1200Å, but its PSF is not diffraction limited and the filters are suboptimal; ideally we would operate at resolutions of ≈ 10 pc for galaxies at 100 Mpc to resolve individual star clusters. This would most likely not be the same camera as for $\langle z \rangle = 1$ surveys, unless the focal length were adjustable.

Sensitivity. To well constrain the LF, we need to reach to a substantially small fraction of the characteristic luminosity, $L_\star$, which also evolves strongly with redshift. We adopt 10% for illustration: $0.1 L_\star^{z=0.3} = 6 \times 10^{40}$ erg s^{-1} [26], and gives a flux of 2×10^{-16} erg s^{-1} cm^{-2}. Reaching $S/N = 5$ (point-source) at the peak sensitivity of ACS/SBC (with filter) would take 22 hours, so substantial improvements in sensitivity would be necessary. Some would doubtless come from a larger, UV-optimized mirror, but higher QE detectors would also be important. Note also that such a program would depend upon sensitivity to low-surface brightness emission – therefore CTE problems on a readnoise-limited CCD are not tolerable.

Field of view. By interpolating between the $z = 0.3$ and 2 LF parameters to $z = 0.8$, we can estimate the density of galaxies. Very roughly we estimate the need to survey 600,000 Mpc^3, which at $z = 0.3 - 1.5$ implies an average area of ≈ 0.1 deg^2, or around the area of the combined goods fields. This would require a FoV that is substantially larger than WFC3/UVIS, but it is not up to the scale of GALEX.

5. Summary and Compatibility with Cosmic Origins Program

We have outlined the need for a sensitive UV-capable mission, carrying at least medium resolution spectroscopic and spectrophotometric capabilities, in order to perform high statistics survey work and detailed studies of the Lyα and UV properties of galaxies over the last 10 billion years. These goals are closely aligned with questions addressed by the COR Program: *How did the first stars influence their environments?*, *How did galaxies evolve?* and *How are the chemical elements dispersed?* Specifically, such observational campaigns at the highest redshifts targeting the first stars, feedback, and chemical enrichment, will be the direct analogues of the observations presented here, but in a regime with much weaker supplementary constraints. Regarding galaxy evolution, the impact of a homogeneous UV study across 10 Gyr should be transparent.

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Galaxy Assembly and SMBH/AGN-growth from Cosmic Dawn to the End of Reionization

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for the *HORUS* & *SFC* science concept teams

Science RFI Response to NASA Cosmic Origins Program

Abstract: In order to address the key Cosmic Origins science question ***"How did galaxies evolve from the very first systems to the types we observe nearby?"***, we propose to the community a *systematic* and *comprehensive* UV–near-IR cosmological broad- and medium-band imaging and grism survey that covers a wide area on the sky in muliple epochs. Specifically we advocate a tiered survey that covers $\sim$10 deg^2 in two epochs to $m_{AB}\sim$28 mag, $\sim$3 deg^2 in seven epochs to $m_{AB}\sim$29 mag, and $\sim$1 deg^2 in 20 epochs to $m_{AB}\sim$30 mag, each at 10σ point source sensitivity. Such a survey would provide spectrophotometric redshifts accurate to $\sigma_z/(1+z)\lesssim 0.02$ and faint source variability measurements for $\gtrsim 5\times10^6$ galaxies and QSOs, and would be an essential complement to *JWST* surveys ($\lesssim$0.1 deg^2 to $m_{AB}\lesssim$31 mag at $\lambda>$1100 nm). This rich data set would allow: (1) study of faint Lyα-emitting and Lyman-break galaxies at 5.5$\lesssim z \lesssim$8 to understand how galaxies formed from primordial density perturbations and to trace the metal-enrichment of the intergalactic medium (IGM); (2) measuring the evolution of the faint end of the galaxy luminosity function (LF) from $z\sim$8 to $z\sim$0 by mapping the ramp-up of Pop II star formation, (dwarf) galaxy formation and assembly, and hence, the objects that likely completed the Hydrogen reionization by $z\simeq$6; (3) direct study of the $\lambda<$ 91.2 nm escape fractions of galaxies and weak AGN from $z\sim$4.0–2.5, during the epoch of Helium reionization; (4) measuring the mass- and environment-dependent galaxy assembly process for $\gtrsim$5$\times$10^6 galaxies from $z\simeq$5 to $z\simeq$0; (5) tracing the strongly epoch-dependent galaxy merger rate and constraining how Dark Energy affected galaxy assembly and the growth of super-massive black holes (SMBHs); (6) the study of $\gtrsim$10^5 weak AGN, including faint variable objects (feeding SMBHs in the faint end of the AGN LF), over 10 deg^2 to measure how SMBH growth kept pace with galaxy assembly and spheroid growth, and how this process was shaped by various feedback processes over cosmic time. The proposed study is not feasible with current instrumentation but argues for a wide-field ($\gtrsim$250 arcmin^2), high-resolution ($\lesssim$0$''$.1), UV–near-IR imaging facility on a 2.4–4 m class space-based observatory.

Over the past decade, our knowledge about the universe at high redshifts has gradually extended to $z\simeq$7 with dozens of quasars discovered in the *SDSS*, *UKIDDS*, and *CFHT-LS* surveys at $z\gtrsim$6 and similar numbers of Lyα emitters. Of particular note are the discoveries of the first "complete" Gunn-Peterson troughs in the spectra of $z>$6 quasars and the WMAP year-7 polarization measurement, which gives a 2σ upper limit to the redshift range of the Pop III star reionizing population of $z\simeq$8–14. The reionization of the universe likely has left its signature on the history of galaxy formation and evolution. It is predicted to cause a drop in the cosmic star formation rate (SFR), and is therefore accompanied by a dramatic fall in the number counts of objects at $z\geq$6.

Since the UV shortward of λ_0=121.6 nm is strongly absorbed by intervening H I, high redshift objects can be selected using the so-called *drop-out* technique. This technique requires filters that bracket Lyα in the relevant redshift range. Recent *i*-, *z*-, *Y*-, and *J*-band drop-out studies with *HST* found significant numbers of $z\simeq$7 candidates, although with non-negligible contamination by low redshift elliptical galaxies and Galactic L- and T-dwarf stars. As evidence mounts that the Hydrogen reionization was largely complete by $z\simeq$6, studies of the z = 6–8 interval — "Cosmic Dawn" —, will be of great cosmological importance.

For how galaxies formed from perturbations in the primordial density field, reflected in the Cosmic Microwave Background (CMB), remains a major problem. While numerical simulations can predict the formation of dark matter halos and their clustering, the formation of stars that render these halos visible is a complex process and hard to predict *a priori*. Thus, there is a great need to

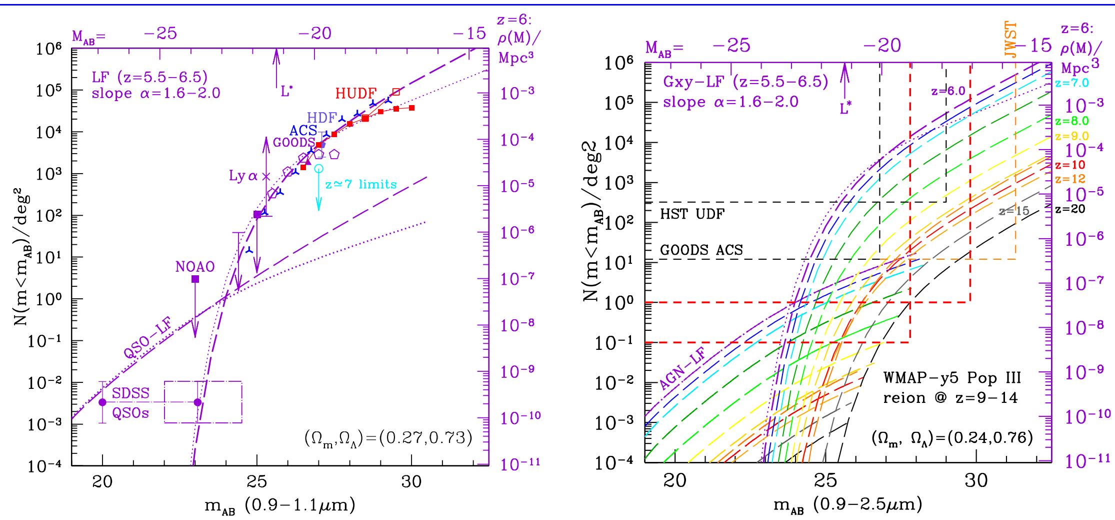

Fig. 1 — (*a*) The integral luminosity function at $z \simeq 6$ from various samples. Left and bottom axes give the observed surface densities and fluxes, top and right axes absolute magnitudes and space densities. The surface density of $z \simeq 6$ QSOs to AB=20 mag from *SDSS* and its extrapolation to fainter fluxes using the measured faint-end slope of the QSO LF ($|\alpha| \simeq 1.6$) are also shown. The faint-end slope of the galaxy LF is significantly steeper: $|\alpha| \simeq 1.8$–2.0 (long-dashed curve). (*b*) The predicted surface density of $z \simeq 7$–8 objects, based on the few candidates from the *HST*/NICMOS and WFC3 surveys (*light blue upper limit in panel* a) and constrained by the total optical depth τ from WMAP, may be an order of magnitude lower than that at $z \simeq 6$, necessitating the very large survey areas proposed here (*red dashed limits*).

study galaxies observationally, at all redshifts. This is especially true at $z \gtrsim 6$, where two major changes took place: (*1*) metal enrichment of the intergalactic medium (IGM), which must have occurred at $z \gtrsim 6$ given the observations of IGM metals even at z=5.7, and (*2*) reionization of hydrogen in the IGM. Since metallicity and ionization change the nature of star formation by changing the available cooling mechanisms, it is *crucial* to push back galaxy samples to $z > 6$.

Surveys for galaxies at $z \gtrsim 7$ are very difficult for many reasons, however. The galaxies are fainter, both because of cosmological dimming and also because of smaller characteristic luminosities and sizes, resulting in low object surface densities (e.g., Fig. 1). It is also important to realize that high redshift galaxy formation is *biased*, resulting in strong spatial variations in number density. For these reasons one would need to survey a large area (at least several deg^2). These searches need to be performed at $\lambda \gtrsim 975$ nm, near and beyond the cut-off of Si CCDs. In the near-IR, there is a tremendous advantage of going to space, with its >100–1000 times darker sky background.

One class of primordial galaxies is easily identified in narrow- or medium-band surveys from their strong, narrow Lyα emission and their diminished flux blueward of this emission. Indeed, Lyα-emitter surveys have proven to be *the* most successful technique to find galaxies at the earliest cosmic epochs. While the Gunn-Peterson troughs are produced by neutral fractions of only 10^{-4} or 10^{-2} (for a homogenous or a clumpy IGM, respectively), the change in number density of Lyα-emitters as a function of redshift traces neutral fractions of the IGM of $\gtrsim$30–80%. A quantitative study based on this principle requires statistical samples of Lyα galaxies in each redshift bin. Ground-based surveys are and will remain severely limited in the volume they can sample due to the necessity to use very narrow bandpass filters (~0.1%) to observe between the strong atmospheric OH lines, which makes them vulnerable to cosmic variance.

The Hubble Ultra-Deep Field (HUDF; Beckwith et al. 2006), our deepest view yet of the distant universe, was collected over 4 epochs that were each ∼1 month apart. Since the data of each seperate epoch still reaches to ∼28 mag, this offered the unique opportunity to study the variability of faint objects on time scales of months, corresponding to 4–5 weeks in the rest-frame. Variability on such time scales betrays the presence of a feeding SMBH within a galaxies' active nucleus (AGN). The redshift distribution of galaxies in a particular early-merger stage and variable objects in the HUDF appear to be similar, which may be a clue to the mystery of how the growth of spheriods and SMBHs has kept pace with the process of galaxy assembly and resulted in the tight Magorrian-relation observed locally. The present statistics are inadequate, however, and the available redshift estimates imprecise. A deep, multi-epoch survey over $\gtrsim$1 deg^2 would allow studying variability of faint objects over a 1000$\times$ larger area on the sky to similar depth, providing vastly superior statistics.

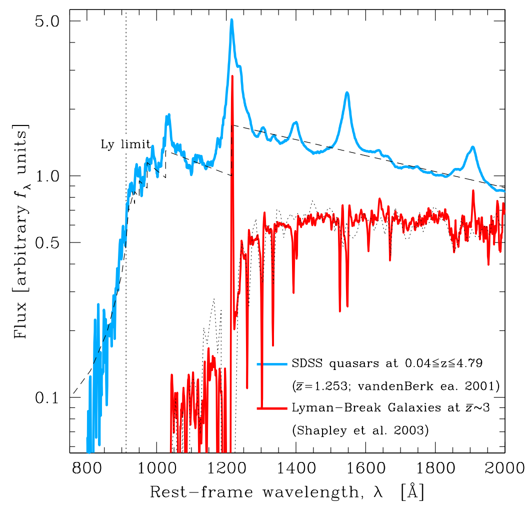

Fig. 2 — Whether the numerous dwarf galaxies or the much rarer AGN finished reionization at $z \simeq 6$ depends critically on the amplitude and faint-end slope of the LF for each population. The steep LF of dwarf galaxies at $z \sim 6$ could provide enough ionizing photons to complete reionization if $f_{esc} \gtrsim 10\%$. Observations in UV–blue filters in the proposed survey will yield escape fractions for $\gtrsim 5\times10^6$ objects.

While *HST* has meant a quantum leap forward, efficient access of the high-z universe is still severely limited by the product $\Omega \times A \times \Delta\lambda$, of small field of view (FoV), limited aperture, and limited wavelength range over which it provides high throughput. A comprehensive study of the galaxy populations from the height of the reionization epoch to the epoch where the present-day Hubble sequence was established, would require a space-based imaging facility that provides:

- ***(1)*** efficient wide-field coverage ($\gtrsim$250 arcmin^2), sufficient to efficiently map areas large enough to average out cosmic variance and find $z \gtrsim 7$ objects with surface densities $\gtrsim$0.1/deg^2;
- ***(2)*** high angular resolution, sufficient to spatially resolve ∼1 kpc sized objects at $0.5 \lesssim z \lesssim 8$ at restframe wavelengths $\lambda_0 >$121.6 nm;
- ***(3)*** sufficient sensitivity to sample both the bright and faint ends of the LFs of galaxies, QSOs, Lyα-emitters and Lyman-break objects from $z \simeq 8$ to $z \simeq 1$, and to $z \simeq 0$ for the Balmer or 400 nm breaks; *and*
- ***(4)*** a sufficiently rich complement of near-UV–near-IR broad- and medium-band filters to provide photometric redshift estimates accurate to $\sigma_z/(1+z) \lesssim 0.02$ and to allow efficient detection of Lyα-emitters from $z \simeq 8$ to $z \simeq 5.5$.

We therefore propose to the community a near-UV–near-IR cosmological broad- and medium-band imaging and grism survey that covers a wide area on the sky in muliple epochs. Specifically we advocate a tiered survey of ∼10 deg^2 in two epochs to m_{AB} = 28 mag, ∼3 deg^2 in seven epochs to m_{AB} = 29 mag, and ∼1 deg^2 in 20 epochs to m_{AB} = 30 mag, each at 10σ point source sensitivity. The use of complementary deep, medium-deep, and wide surveys is a proven strategy to maximize the scientific return for the investment in telescope time. Such surveys would provide spectrophotometric redshifts accurate to $\sigma_z/(1+z) \lesssim 0.02$, faint source variability for $\gtrsim 5\times10^6$ galaxies and QSOs, and a probe of the universe at Cosmic Dawn when less than half of the hydrogen had been ionized. It would constitute an essential complement to deeper *JWST* surveys $m_{AB} \lesssim 31$ mag at $\lambda > 1100$ nm and $z \gtrsim 8$) over far smaller areas ($\lesssim 0.1$ deg^2).

In the following, we summarize the science goals for each of the themes of this survey.

Key scientific themes that have arisen from recent advances

Evolution of the Faint-end Slope of the Dwarf Galaxy Luminosity Function The faint-end slope of the galaxy LF is systematically steepening at higher redshifts, reaching a slope $|\alpha|$=1.8–2.0 at $z \sim 6$. This implies that dwarf galaxies collectively could have produced a sufficient number of ionizing photons to complete the reionization of Hydrogen in the universe by $z \sim 6$. This critically depends on the escape fraction, f_{esc}, of far-UV photons from faint dwarf galaxies. The proposed survey, in particular the UV–blue broad-band filters, could answer this question for statistically meaningfull samples per redshift bin. It furthermore depends on the evolution of the amplitude of the dwarf galaxy LF and whether or not there could be a significant scatter in the faint-end slope due to clustering. The surface density of $z > 7$ objects appears to be an order of magnitude lower than that at $z \sim 6$, but these wide-area surveys would unambiguously answer these questions.

Tracing the Reionization History using Lyα-Emitters Observations so far have failed to settle the issue of whether the amplitude of the Lyα-emitter LF changes between $z = 5.7$ and $z = 6.5$, or as extrapolated from objects and candidates at $z \gtrsim 7$. The proposed medium-band surveys will derive their LF as a function of redshift at $z \gtrsim 5.5$ over a wide area for large statistical samples and definitively address how the reionization of the IGM progressed over time. Furthermore, the data will allow measuring the ages and clustering properties of Lyα-emitters, and, via the faint-end slope of their LF, their contribution to the budget of ionizing photons. The latter is a complementary probe of cosmic reionization compared to the counting experiment (LF amplitude).

Light Profiles of Dwarf Galaxies Around Reionization The average radial surface brightness profile derived from stacked, intrinsically similar, $z \simeq 6$, $z \simeq 5$, and $z \simeq 4$ objects extracted from the *HST*/ACS HUDF show a deviation from a Sersíc profile at progressive larger radii. If interpreted as a virial radius, in a hierarchical growth scenario, this would imply dynamical ages for these dwarf galaxies of a 0.1–0.2 Gyr at $z \simeq$ 6–4. These 'dynamical' limits to their ages are comparable to age estimates based on their SEDs, suggesting that the starburst that *finished* the H reionization at $z \simeq 6$ may have started by a global onset of Pop II star formation at $z \simeq$ 6.5–7, or $\lesssim 200$ Myr before $z \simeq 6$. The proposed surveys will yield light profiles, color gradients, and dynamical states of $\gtrsim 10^5$ dwarf galaxies at $0.5 \lesssim z \lesssim 7$, and provide constraints to their ages from their SEDs and, for a subset, also from systematic profile deviations.

Lyman-continuum Escape Fraction of Dwarf Galaxies and Weak AGN At $z \simeq 6$, the Lyman-continuum escape fraction is likely somewhat larger than the 10–15% measured for Lyman-break galaxies at $z \simeq$ 3–4, reflecting the lower metallicity at larger redshifts. If indeed dwarf galaxies, and not QSOs, dominated the late stages of reionization, then these objects cannot have started shining pervasively much before $z \simeq$ 7–8, or no neutral H I would have been detected in front of $z \simeq 6$ *SDSS* quasars. Hence, one would expect to find a down-turn in their LF amplitude at $z \gtrsim 6.5$ — or a rapid onset of the cosmic SFR from $z \simeq 8$ to $z \simeq 6$, which may be identified with the onset of dwarf galaxy formation. The proposed surveys will provide a unique glimpse into this era of 'Cosmic Dawn', where the first global IMF of Pop II stars in dwarf galaxies started forming.

The Process of Hierarchical Galaxy Assembly The process of galaxy assembly may be directly traced as a function of mass and cosmic environment in the redshift range $0.5 \lesssim z \lesssim 5$. The *HST* Deep Fields have outlined how galaxies formed over cosmic time, by measuring the distribution over structure and type as a function of redshift. Sub-galactic units appear to have rapidly merged from $z \simeq 6$–8 to grow bigger units to $z \simeq 1$. Galaxies of all types formed over a wide range of cosmic time, but with a notable transition around $z \sim 1.0$. Merger products started to settle as galaxies with familiar morphologies, and evolved mostly passively since then. The fine details of this process still elude the *HST* surveys, because of inadequate spatial sampling and/or depth, and because its FoV is too small to provide sufficient statistics. The proposed imaging through multiple near-UV–near-IR filters and grism(s) would yield robust spectrophotometric redshift estimates for $\gtrsim 5 \times 10^6$ galaxies with $m_{AB} \lesssim 28$–30 mag, and allow an analysis of their stellar populations (through population synthesis modeling) and their structure on spatial scales $\lesssim$ few kpc.

The Epoch-dependent Merger Rate of Galaxies With robust photometric redshift estimates, it has become feasible to meaningfully trace the pair fraction and galaxy major merger rate to very faint limits ($m_{AB} \gtrsim 27$ mag). From *HST*/ACS flux limits and panchromatic SED fitting, the currently available surveys have shown a mass completeness limit for $z \lesssim 2$–4 for $M \gtrsim 10^{10.0}\,M_\odot$ for primary galaxies in a pair and $M \gtrsim 10^{9.4}\,M_\odot$ for secondary galaxies. The proposed surveys would allow mapping the *entire* epoch-dependent merger history to at least 3 mag fainter. This would yield the galaxy merger density as a function of total mass, mass ratio, redshift, and local overdensity and do so for $\gtrsim 10^6$ galaxies at $m_{AB} \lesssim 28$–30 mag over a much wider range of masses ($10^{9.8}\,M_\odot \lesssim M \lesssim 10^{11.5}\,M_\odot$) and for redshifts $0 \lesssim z \lesssim 7$.

The Growth of Super-Massive Black Holes Through a multi-epoch variability study, the proposed surveys will be able to measure the weak AGN fraction in $\gtrsim 10^5$ field galaxies to $m_{AB} \lesssim 28$–30 mag at $z \lesssim 8$ directly, and so robustly constrain how exactly growth of spheroids and SMBHs kept pace with the process of galaxy assembly. The panchromatic imagery and robust spectrophotometric redshifts will allow decomposition of the AGN light from that of the underlying galaxy. This science theme also relies on a stable PSF and proper PSF sampling.

Broad Design Considerations Driven by this Science

Resolution — In order to spatially resolve kpc-sized objects at $0.5 \lesssim z \lesssim 8$ at rest-frame wavelengths $\lambda_0 > 121.6$ nm, a resolution $\lesssim 0\farcs04$ would be required.

Wavelength agility — pan-chromatic wavelength coverage from near-UV through near-IR for a comprehensive understanding of the star-formation and assembly histories of galaxies, and to access Lyα emission redshifted to $z \sim 8$.

Wide-field focal plane arrays — these are presently not at sufficiently high TRL; investment is needed to improve yields, provide cheaper devices and high-throughput assembly and testing to enable economies of scale. (Such an investment would not just benefit the science proposed here)

Coatings — an investment in improving the relatively poor broad-band performance of optical coatings of telescope mirrors in the UV, with typical reflectances below 85% (Al+MgF_2) directly results in a large increase in throughput for a given telescope aperture, or more affordable missions for a given sensitivity requirement.

Dichroics — most photons collected by telescopes are rejected by bandpass filters. Dichroic(s) potentially double (or even triple) the observing efficiency of astronomical observatories (e.g., *Spitzer*/IRAC) and allow tuning downstream optics and detectors for more optimal performance, avoiding compromises inherent in forcing performance over more than an octave in frequency.

The proposed science program does not stand alone, but must build on a strong understanding of the physics of the star formation process in various environments, theoretical insights in cosmological models of reionization and structure growth, as well as synergy with both higher-resolution near-IR AO observations with next-generation giant-aperture telescopes, and deeper observations in the near- and mid-IR with *JWST* over small fields of view.

Combination of a large collecting area, very wide field of view, high angular resolution, wavelength agility and/or multiplexing advantage would allow orders of magnitude more efficient UV–optical observations of star formation, galaxy assembly, and SMBH-growth processes and, moreover, open up a new domain in discovery space near and far. Injection into L2 (or an Earth Drift-Away orbit) provides dynamical and thermal stability, and doubles efficiency over LEO orbits and, hence, lowers cost per hour of observation (all other variables being equal). Large focal plane array (dozens to hundreds of individual CCD or CMOS detectors) and dichroic camera (simultaneous observation in two or more channels of the same field of view) technology is better matched to the collimated beams provided by optical telescope assemblies and less wasteful in terms of collected photons, maximizing science output and especially benefitting survey science with a lasting legacy beyond the nominal duration of a mission. Survey science allows discovery of very rare objects amongs billions and billions, the positions an properties of which may not be knowable a priori.

Four central questions to be Addressed

(1) How did reionization progress during the era of ‘Cosmic Dawn’? Was it an extended, a rather abrupt, or even a multiple event?

(2) How did the faint end of the galaxy luminosity function evolve from the onset of Pop II star formation till the end of the reionization epoch?

(3) How exactly did AGN and SMBH growth keep pace with the process of galaxy assembly? How did AGN growth decline with the galaxy merger rate and the cosmic SFR?

(4) Was there indeed an epoch of maximum merging and AGN activity around $z \simeq 1$–2 for the more massive galaxies, before the effects from the increasingly dominant Dark Energy kicked in? How does this peak epoch depend on galaxy total mass or bulge mass, and (how) does this support the galaxy downsizing picture?

Response to NASA RFI NNH12ZDA008L
A UV/Optical/Near-IR Spectroscopic Sky Survey for Understanding Galaxy Evolution

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Jeffrey Kruk, Jane Rigby (NASA's GSFC), Massimo Roberto (STScI)
10 August 2012

Abstract

We outline the scientific benefits of a very large UV/optical/near-IR spectroscopic survey for understanding the evolution of galaxies, circumgalactic medium, and intergalactic medium in the era of galaxy assembly (z>1).

Scientific Goals

The prime objective of NASA's Cosmic Origins (COR) Program is summarized by the question, How did we get here? Important elements of this overarching question include: 1) How did galaxies evolve into the types we observe "in the here and now", and 2) When did supermassive black holes form and grow, and how have they have affected the lives of their host galaxies? 3) How are chemical elements distributed in galaxies and dispersed in the circumgalactic medium (CGM) and intergalactic medium (IGM)? 4) How does baryonic matter flow from the IGM into galaxies?

Hubble has already made great strides towards answering these questions. What we need now is to *understand* what processes are responsible for the evolutionary paths we see. Take for example, the first question on galaxy evolution. Thanks to the Hubble Space Telescope Deep Fields and surveys such as Galex and the Sloan Digital Sky Survey, we know that galaxies were more or less assembled by redshift z=1 (look-back time=7.7 Gyr), and most of the stars in the universe formed before z=1. The scientific frontier now is to look back further to z>1 galaxies to observe how galaxies evolved to form the familiar Hubble sequence of spirals and ellipticals and to establish which processes were responsible. Learning *how* galaxies evolved to the present day is the objective of WFIRST's near-IR *imaging* survey [1,2]; learning *what processes drove the evolution* is needed to *understand* galaxy evolution.

Scientific Investigation

Experience with the Sloan Digital Sky Survey of relatively nearby galaxies (z~0.1) suggests a s*pectro-scopic* survey of a few times 10^5 to 10^6 galaxies at z>1 is essential for identifying the processes driving galaxy evolution, because only spectra can provide accurate redshifts, information on the kinematics of galaxies, physical conditions of the ISM, evolution of the mass-metallicity relation, co-evolution of black holes, etc. [3, 4]. Large numbers of galaxy spectra must be obtained in order to disentangle the effects on galaxy formation and evolution of accretion, interactions and merging, star formation and feedback, black hole growth and feedback. Similarly, a wide variety of environments must be studied in order to identify the processes that regulate cooling, condensation, and star formation. Thus, a wide-field telescope with a multi-object spectrograph(s) is needed.

Both the rest-frame UV and optical are rich in spectral diagnostics. The UV provides sensitivity to recent star formation, the properties of young stellar populations, the properties of the gas (column density and ionization state, metallicity and optical depth of the neutral gas, inflows and outflows, etc.), and properties of the dust component of galaxies [5]. The optical region provides accurate redshifts through sharp emission lines or the D4000 break, the stellar mass, and metallicity of the ionized gas. For z>1 galaxies, the observed wavelength range of these important diagnostics is 0.2-1.7 μ -- not quite the full expanse of Hubble (0.12-2.5 μ). This spectral range is covered well by a UV/optical/near-IR telescope with large-format CCD's and MCT detectors, just like on Hubble.

Note that the scientific benefits of the UV/Vis and near-IR are complementary; they usually do not overlap. For example, a UV/Vis spectrograph is uniquely capable of tracking Lyman α in the IGM and CGM around z>1 galaxies, while a near-IR spectrograph is uniquely capable of providing stellar mass of z>1 galaxies unbiased by star formation or dust. The point is that *spectroscopy over a wide wavelength range, 0.2-1.7 μ, viewing the same galaxies is required to obtain the full set of diagnostics that would lead to a physical understanding of galaxy evolution.* The Subaru/Prime Focus Spectrograph [3] is a first attempt at understanding galaxy evolution from simultaneous multi-object spectroscopy, but with a truncated spectral range, 0.38 – 1.3 μ, it cannot, for example, sample the all-important H I Lyα line in galaxies at z<2.2, or the Hα emission line in galaxies at z>1.0. A space-based mission is required to obtain all the important diagnostics.

Previous survey results [4] indicate that there are ~3,000 galaxies per square degree brighter than L* in each of 5 redshift shells: [0.6-0.8, 0.8-1.05, 1.05-1.35, 1.35-1.65, 1.65-1.95]. The rest-frame r-band flux of an L* galaxy at each of these 5 redshifts is [4.7, 2.4, 0.93, 0.50, 0.25]x10^{-18} erg/s/cm^2/A, respectively. These galaxies are faint! Worse, the zodiacal background is bright. Even worse for slitless spectrometers, the observed zodiacal background will be extremely bright because the background at each pixel is the integral of the zodi spectrum over the bandpass. The zodi may not be a problem for the slitless spectrograph on WFIRST, because it only needs to measure the redshift of relatively bright emission lines (~1x10^{-16} erg/s/cm^2), but it is a disaster for a telescope that needs to measure faint continuum fluxes (~1x10^{-18} erg/s/cm^2/A) of z>1 galaxies. The most promising approach is thus a multi-object slit spectrograph, employing a micro-shutter array or digital micro-mirror device for object selection.

Areas for Further Study

It is not clear what size telescope is needed or what difference-size telescopes can accomplish. To answer these questions, it will be necessary to carry out realistic simulations that will help us to evaluate the scientific yield of telescopes with diameters (0.5 m to 2.4 m) and spectral resolving power. Rough measures of the science yield are the time it takes to acquire satisfactory spectra (S/N>7 per resolution element) for 10^6 galaxies at z>1, the highest redshift shell that can be reached, and information on line widths.

Scientists involved in Euclid, WFIRST, or Subaru/Prime Focus Spectrograph have already carried out similar simulations. We would follow them in basing these simulations on the COSMOS Mock Catalog (CMC; [6]) of over 500,000 galaxies with redshifts in the range, z=0-6. Entries in the catalog give redshift, galaxy type, extinction, half-light angular radius, continuum fluxes in B, V, R, I, and K, as well as fluxes of important emission lines. The first step would be to predict the UV/optical/near-IR spectrum of each galaxy in the CMC using model stellar-population spectra + CMC emission-line strengths. Next, for each telescope aperture and associated slit mechanism, we would determine which galaxies can be observed and how many. Then, we would determine the time needed for various types of measurements, e.g. redshift, continuum fluxes, colors, and spectral breaks, and emission-line fluxes and line widths. Finally, we would analyze the data to estimate the science yield described by (1) the time it takes to acquire satisfactory spectra (S/N>7 per resolution element for 10^6 galaxies at z>1, (2) the highest redshift bin that can be reached, i.e. how far back in time can we look, and (3) possibility of measuring useful line widths. We would also use a modified version of the WFIRST exposure-time calculator [7] to predict the image properties and emission-line fluxes of galaxies in the CMC.

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An Optical and Ultraviolet Cosmological Mapper

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Why Mapping the Largest Scale of the Universe?

Astronomical observations have become a vital tool for studying fundamental physics, and advances in fundamental physics are now essential for addressing the key problems in astronomy and cosmology. The past 15 years have been a period of tremendous progress in cosmology: we now have a simple cosmological model that fits a host of observations. One of the strangest *features* of our current cosmological model is the observation that the expansion rate of the universe is accelerating. This late-time acceleration implies either the existence of dark energy (DE), a substance whose equation of state is bizarre or the break down of Einstein's gravitation theory (GR) on cosmological scales. Understanding the cause of cosmic acceleration is one of the great challenges of physics. Another great *unknown* is the origin of primordial perturbations that grew to form the large scale structures (LSS) that we observe today, i.e. what physics is describing the universe when it was 10^{-30} second old and its temperature was about 10^{16} GeV.

Observations of large-scale structure have played an important role in developing our standard cosmological model and will likely play an essential role in our investigations of the origin of cosmic acceleration and cosmic origins. *Novel use of optical and UV observations potentially offer very potent avenues to address this issue in a definite manner.*

Working in the "intensity mapping regime" – large scale, low spatial resolution, moderate spectral resolution – optical and UV surveys offer a potentially very powerful, yet economical, avenue to map cosmological scales. The idea consists in mapping the aggregated line emission of many galaxies in a given frequency/redshift range rather than the emission of individual galaxies. To not aim at resolving individual galaxies naturally allows the use of a smaller telescope and also increases the signal strength, thus decreasing sensitivity requirements.

The matching between frequency and redshift requires that the line being mapped is well identified. Observing at radio frequencies and focusing on the bright 21 cm HI line, this idea lead to a flurry of experimental development and already pioneering measurements (Chang *et al.* 2010, Masui *et al.* 2012). These developments aim either at mapping the epoch of reionization or at mapping large scales at lower redshift to characterizing DE (Peterson *et al.* 2009). Recently, the use of other lines such as CO or CII emission states has received some interest as a probe of reionization and is also motivating several observational efforts (Lidz *et al.* 2011, Gong *et al.* 2011, Visbal *et al.* 2010, Gong *et al.* 2012).

An obvious candidate line to extend this technique to the optical and UV window is the hydrogen Lyman-α line (Lyα). Indeed, to map this 121.6 nm emission line over the full optical and ultraviolet window would allow us to map continuously a redshift range up to z$\sim$ 6. To extend it to slightly larger wavelengths would lead to an interesting probe of the epoch of reionization up to $z \sim 12$ (Silva *et al.* 2012, Pullen *et al.* 2012). The observational set-up required to perform this large scale mapping is quite modest.

Some Modest Observational Requirements

To briefly illustrate what such an experiment would take, we will set as a simple requirement that we want to map comoving scales up to 1 (10) Mpc/h up to $z = 6$. This naturally sets the required angular resolution since spatial resolution perpendicular to the line of L in Mpc/h indeed requires an angular resolution given by $\Delta\theta = L/D_A(z = 6)$ where D_A is the comoving angular diameter distance up to $z = 6$. Assuming a standard cosmology, it is about 0.6 (6.) arcmin. for L= 1 (10) Mpc/h. A telescope with a diameter of a few tens of cm would achieve this while providing a large collecting area. Our target redshift window requires a frequency coverage from 121.6 nm up to 850 nm. Targeting an identical spatial resolution along the line of sight leads to a frequency resolution, $R = 2\pi c(1 + z)/H(z)/L$, of 2200 (220). As such, it is clear that such a survey would have rather modest needs as compared to more contemporary surveys.

Our estimates lead to a line flux for the Lyα line varying from 5×10^{-19} to 2×10^{-16} erg.s^{-1}.cm^{-2}. arcsec^{-2} when the source moves from $z = 6$ to 1. Such measurements are likely to be sky background limited. The very dark near and far UV sky background is dominated by scattering of starlight by interstellar dust at a continuum level of order 400-600 photons.cm^{-2}.(s.sr.A)$^{-1}$ at the galactic poles, and increases toward the galactic equator (Murthy *et al.* 2010). The sensitivity of an instrument designed to measure the diffuse Lyα emission from large scale structures depends on the aperture, spectral resolution, throughput, sky background, detector background and other factors. Although it is premature to offer a detailed description of the instrument configuration and resulting exposure time, preliminary calculations indicate that high signal to noise ratio can be achieved in relatively short exposures with a modest aperture, assuming high instrument throughput and sky background limited observations. Note that the access to space would be critical to access the large scales of interest, provide good flat-fielding and avoid atmospheric fluctuations.

The Need for Spectral Deconvolution

For the sake of illustration, we so far made the simplifying assumption that we can directly match a frequency to a given redshift. It is obviously true only in the limit where one line dominates, as is the case for the 21cm radio line. In the frequency coverage of interest to us, an abundance of emission lines will contribute and requires an extra-step to separate the measured emission at all frequencies into redshift slices. We need to perform a spectral deconvolution (Holder & Doré 2012).

The intensity as a function of wavelength is generally a superposition of many sources along the line of sight at a variety of cosmological redshifts:

$$I(\nu) = \int dz f(z) j(\nu, z) \ , \tag{1}$$

where $f(z)$ indicates the flux per unit redshift and j is the redshifted spectrum. In the simple case of a non-evolving rest-frame spectrum j_{rest}, this can be written as

$$I(ln\nu) = \int dz f[ln(1+z)] j_{rest}[ln\nu + ln(1+z))] \ . \tag{2}$$

This is a pure convolution, where the rest frame SED has been convolved with the redshift distribution, both of which are unknown quantities of interest. Different positions on the sky, however, will have different $f(z)$ (from fluctuations in large scale structure) but similar j_{rest}, allowing a separation of these two quantities. This is a cosmological analog of the Fourier quotient method of stellar kinematics (Sargent et al. 1977), with the added feature of using multiple lines of sight to disentangle the rest spectrum and that the dominant line ratios are very perfectly known.

Cosmological evolution of the SED will complicate this simple picture, but evolution with redshift should be modest over the scales of interest; a parameterized redshift evolution that is subsequently marginalized over should be sufficient to minimize this source of confusion. Ultimately, we expect to be able to separate deconvolution in angular, redshift and $\ln\nu$ space from which we will be able to extract the 3D matter power spectrum as a function of scales. This last stage will require the determination of an effective luminosity weighted bias as function of redshift. This will be possible using the measurement of redshift space distortion on very large scales using techniques developped for spectroscopic galaxy survey (Hamilton 1997, Kaiser 1987, White *et al.* 2008).

Cosmological Implications

We propose a modest experimental set-up that allow to map in the optical and UV the full sky as a function of redshift up to $z \sim 6$. While it is clear that such a survey would have rather modest needs as compared to contemporary cosmological surveys, its fundamental physics or astrophysics impact could nevertheless be paramount.

We could basically produce a three-dimensional map of the matter distribution throughout our universe. Our three dimensional resolution is enough to probe all the modes in the quasi-linear regime which are typically used for doing cosmology. As such, to compare the cosmological information content of our survey, it is fair to compare its volume (directly proportional to the number of modes) to other current and future surveys. Roughly speaking, mapping 8,000 square degrees up to $z \simeq 0.7$, the SDSS-I survey has mapped around 5 $[\mathrm{Gpc}/h]^3$, the current BOSS survey will map 8,000 square degrees up to $z \simeq 0.9$, that is about 9 $[\mathrm{Gpc}/h]^3$. The ESA/NASA Euclid is set to cover 15,000 square degree up to $z \simeq 2$, that is about 80 $[\mathrm{Gpc}/h]^3$. The mapper we are proposing, mapping the full sky up to $z \sim 6$ would cover about 800 $[\mathrm{Gpc}/h]^3$.

This mapping would thus turn into orders of magnitude improvements in the constraints on cosmological parameters expected from the experience mentioned above. To access large (linear) scales in redshift space would enable the joint determination of the expansion history and the growth rate of structures. The former stems from the measure of the baryonic acoustic oscillations scale (Eisenstein *et al.* 2005), the characteristic scale imprinted by the sound waves within the primordial plasma in the Early Universe, and use this cosmic ruler to determine the hubble constant as a function of redshift. The latter results from the impact of cosmic velocity on the measured redshift, which depends upon the growth rate of structures (Kaiser 1987). To be able to probe both the acceleration and the growth is critical: if cosmic acceleration is caused by DE, then there is a simple relation between the two. Deviations would imply the breakdown of GR, a nearly century-old pillar of modern physics (Weinberg *et al.* 2012).

This mapping would also provide exquisite constraints on the nature of the initial conditions and in particular the primordial non-Gaussianity. The sensitivity of such an experiment would be such that the primordial non-Gaussianity would be easily measured, independently of the Inflation model considered, a feat achieved by no other cosmological planned experiment. The combination of small and large scale power would provide a precision tests of inflation, since it would extend the lever arm for constraining the spectral index and its running for the power spectrum of inflationary seed fluctuations. It would also provide an ideal test-bench to test general relativity on cosmological scales. Finally, the exquisite shape measurement of of the power spectrum and its redshift evolution would allow to constrain neutrino mass to a tenth of an eV.

Such a survey would certainly contributes towards NASA's strategic goal 3.4 "*Discover the origin, structure, evolution, and destiny of the universe*" (NASA Science plan, p.161).

We'll directly address the suggested "Decadal Outcomes" outlined in NASA's science plan to "*1. Progress in understanding the origin and destiny of the universe ... and the nature of gravity*" and "*2. Progress in understanding how the first stars and galaxies formed, and how they changed over time into the objects we recognize in the present universe.*" (NASA Science Plan page 161). This proposal also addresses six of the key questions identified in the Atro2010 report "New Worlds, New Horizons in Astronomy and Astrophysics (NAS Decadal Survey): *Why is the universe accelerating?*, *What is the fossil record of galaxy assembly from the first stars to present?*, *What are the connections between dark and luminous matter? How do cosmic structures form and evolve?* and *"How did the universe begin?"*.

We would be definitely be interested in participating and presenting our science objectives and investigations at a workshop, if invited.

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Exoplanet Science of Nearby Stars on a UV/Visible Astrophysics Mission

1 Objective

Exoplanet science is an exciting field that attracts many young scientists, stimulates a flood of science papers, and yields new exoplanet discoveries daily. Moreover, it addresses one of the fundamental questions of our civilization: "Are we alone?"

Exoplanet science includes (1) discovering exoplanets, (2) measuring their properties, and (3) studying the processes of their origin and evolution. The answers will complete the astrophysical picture of our origins, from the Big Bang, to galaxy formation, star formation, and finally planet formation. However, exoplanet science can go further, because we also have the ability to detect evidence of life on a planet. So while it addresses traditional astrophysics concerns, it also uniquely connects directly with people and their view of themselves in the universe.

Growth in exoplanet science can be measured by the increasing number of refereed publications in the field. In the 20 years up to about 1994, the number of science papers per year had a doubling time of about 11 years. In the next decade, up to about 2004 when exoplanet discoveries began to accumulate, the doubling time shrank dramatically, to about 3 years. In the time since about 2004, the field has matured, and is doubling about every 5 years. The current rate of publication is about 1700 papers per year.

For all these reasons, exoplanet science is a cornerstone of NASA's strategic plan. The Astrophysics Division asks "What are the characteristics of planetary systems orbiting other stars, and do they harbor life?" The Cosmic Origins Program (COR) asks "What are the mechanisms by which stars and their planetary systems form?" The Exoplanet Exploration Program (ExEP) seeks "to advance our understanding of planets and planetary systems around other stars" and "to extend this exploration to the detection of habitable, Earth-like planets around other stars, to determine how common such planets are, and to search for indicators that they might harbor life" (2010 Science Plan, p. 62).

Observations of exoplanets can be approached by a range of techniques, from small to large in scope. Successful ground-based projects include radial velocity observations, searches for transiting planets, transit timing observations, spectroscopy of transiting planets, gravitational microlensing searches, and direct imaging of young gas giant planets in large-diameter orbits.

The closest 100-200 solar-like stars are a prime hunting ground for exoplanet detection and characterization and to search for signatures of life. It is here that direct-imaging techniques find their best use. By giving us an opportunity for close-up study of these planets, direct imaging promises a wealth of new information. It is applicable to a wide range of planetary systems, including analogs of solar system planets from Venus to Saturn.

A space telescope is required for direct imaging of rocky planets in solar system analogs around nearby stars, because atmospheric blurring makes it essentially impossible to achieve the necessary contrast with current ground-based telescopes. Since both ultraviolet astronomy and direct imaging of exoplanets require space platforms, and since both sciences require a nominally conventional telescope, it makes sense to investigate whether these fields could share a common telescope mission, essentially sharing the cost burden of the central facility. This white paper explores the concept of such a shared space mission.

2 History of COPAG-ExoPAG collaboration

The following is a summary of ongoing discussions between the Exoplanet Program Analysis Group (ExoPAG) and the Cosmic Origins Program Analysis Group (COPAG) beginning with a meeting on April 26, 2011 at the Space Telescope Science Institute (Baltimore, MD),[*] on the topic of compatibility of the ExoPAG and COPAG mission concepts. This meeting was also summarized in a public meeting of the ExoPAG in June 2011 (Kasting[†]). This was followed by a joint meeting of the full ExoPAG and COPAG in January 2012 at the AAS meeting.[‡]

The ExoPAG continues to share the COPAG's interest in a "flagship class" optical and UV telescope of 4m diameter and larger, which could serve as a key tool in the effort for direct detection and characterization of planets down to Earth size orbiting nearby F, G, and K stars. Pursuant to that, we have assembled a draft set of Level 1 science requirements for a visible light direct detection mission, often called Terrestrial Planet Finder or TPF. These have been developed in discussions of Study Analysis Group 5 (SAG5) on open teleconferences, but have not yet been formally approved by the community that contributed to them. This draft report is given as an appendix below, and its key features are summarized here.

Two candidate implementations of direct detection and characterization of exoplanets in visible light are an internal coronagraph instrument and an external starshade. The choice between them is an extremely complex one, for which we don't yet have enough information. But briefly,

- the starshade option requires a separate spacecraft to block the host-star's light, which entails some significant engineering challenges; but it is compatible with a completely generic optical-UV telescope with simple instruments.
- the internal coronagraph involves a more complex science instrument, but with promising technology readiness, and enjoys single-spacecraft operation; but its stability requirements on the telescope are very challenging, with corresponding technology development challenges. And some coronagraph types are incompatible with obscurations and segmentation.

In light of these uncertainties, and the very different strengths and weaknesses of these options, we have selected an unusual way of defining our science requirements. This is reflected in the structure of Musts and Discriminators rather than Minimum and Baseline mission requirements, as explained in the Appendix. This structure and the corresponding decision process allow a thoughtful and deliberate decision among options that can be difficult to compare sensibly any other way.

[*] http://exep.jpl.nasa.gov/exopag/exopagCopagJointMeeting/ and http://cor.gsfc.nasa.gov/copag/mtgs/stsci_apr2011/

[†] http://exep.jpl.nasa.gov/files/exep/Kasting_Review%20of%20ExoPAG_COPAG.pdf

[‡] http://exep.jpl.nasa.gov/exopag/exopag5/agenda/ near the bottom.

3 Description of Exoplanet Science Investigation

Direct imaging of nearby planetary systems will enable three broad science areas: (1) detection of individual exoplanets; (2) spectral characterization of those exoplanets, including searching for signs of life; and (3) investigation of the origin and ultimate fate of planetary systems.

The detection of individual exoplanets requires a high contrast imaging capability (e.g. internal coronagraph or external starshade), and can be accomplished with only a few snapshot images of the area around a star. (Multiple images are needed, to verify that the planet image moves with the star and is not a background object.) These discovery images are sufficient to catalog and identify planets for follow-up study, and for initial estimates of planet type, using rough metrics such as brightness and color.

The spectral characterization of individual exoplanets begins with a longer observation for modest resolution spectroscopy ($\lambda/\delta\lambda \approx 70$-$100$), and should be followed by observations over a time span approaching or exceeding an orbital period, to obtain position, photometry, and spectroscopy as a function of time. The resulting treasure trove of data gives us the key orbital elements (semi-major axis, inclination, eccentricity), a more solid determination of the type of planet (gas giant, ice giant, terrestrial), an estimate of the state of the atmosphere (gas composition, clouds, variability), a possible estimate of weather (variability of atmosphere), an informed guess as to the mass (combining the type of planet and brightness, with models), an accurate estimate of the mass (intensively applying radial velocity measurements), an estimate of radius and density (from brightness, type, mass, and models), and for terrestrial planets an estimate of habitability (temperature, water abundance, likelihood of a solid surface) and signs of life (oxygen, ozone, chlorophyll spectra).

The investigation of the origin and evolution of planetary systems combines the information from the detection and characterization phases with our experience with the thousands of planets and candidates in the Corot, Kepler, RV, and gravitational microlensing surveys, and our knowledge of the specific planet-disk and planet-planet orbital interactions that are implied from many of the precise timing events from Kepler. This area also draws on knowledge of the masses, orbits, and orbital evolution within our solar system. Theoretical modeling is obviously of fundamental importance in tying together all these strands. The goal of this phase of investigation is a unifying picture of the birth, evolution, and ultimate fate of planetary systems. This goal will elevate planetary science to a level of understanding and completeness comparable to that of present-day stellar astrophysics, galactic evolution, and cosmology.

4 Ultraviolet-Exoplanet Synergy

There are mission synergies as well as scientific synergies connecting ultraviolet and exoplanet sciences. The most obvious of these is sharing a space telescope mission. Relevant mission aspects include telescope size, telescope type, and orbit.

There is no strict requirement on telescope size from either science area, because both sciences have outstanding science that they can pursue in each size range. For example, for 1-2 m diameter telescopes, UV science could gain compared to previous missions if the optical efficiency were improved, a realistic possibility given current work in detectors and mirror coatings. Likewise exoplanet science could pursue visible-wavelength direct imaging and spectroscopy of giant planets beyond the snow line, and could expand that harvest by also imaging in the UV, a little-explored spectral region for exoplanets. With a 2-4 m telescope, UV science would further benefit from the improved angular resolution, pushing well beyond current capabilities. Likewise exoplanet science would gain the ability to directly image smaller planets well inside the snow line, reaching as far as the habitable zone in many stars, thus enabling direct searches for habitable terrestrial planets. And in the 4-8 m and larger class, both sciences would gain tremendously from the increased grasp of more distant objects, and the improved signal strength that would drastically reduce observing times for exoplanets, for example. (The Appendix shows our first effort to develop mature requirements for exoplanet missions, beginning with the largest of these classes.)

Regarding telescope type, both sciences could utilize conventional on-axis telescopes, but both would benefit substantially from the reduced diffraction of an off-axis system. One stumbling block to date has been the lack of a mirror coating that would provide high reflectivity at wavelengths as short as 100 nm, while at the same time giving acceptably small polarization effects in the visible, as needed for internal coronagraphs; however research in this area is promising, so coatings are not expected to be a fundamental problem.

UV and exoplanet sciences would both benefit from an L2 or drift-away orbit. For UV science, it is advantageous to be far from the Earth's geocorona, and for exoplanet science the key requirement is a stable thermal environment (for an internal coronagraph) or a free-flyer friendly environment (for an external coronagraph).

There are additional science synergies of mutual benefit. If simultaneous UV and exoplanet science observations are implemented, then the UV fields around nearby exoplanet target stars can be imaged with extremely deep exposures, permitting the UV equivalent of the Hubble deep fields. And exoplanet science can capitalize on the capability of the telescope optics to deliver UV images to the coronagraph detectors and spectrometers, thus allowing a search for UV-active atmospheric constituents, for example ozone on a terrestrial planet.

5 Telescope Characteristics and Drivers for Exoplanet Science:

It is premature to attempt a detailed discussion of how a flagship-class starshade or coronagraph mission might impact a flagship COR mission. But these are the principal features of our telescope requirements:

- Wavelength passband 0.5 to 0.8 µm, with extra value for extending to 1 µm and toward the UV. (Much of the burden for providing this passband falls on the exoplanet instruments themselves.)
- Aperture diameter of order 4 meters and larger. This could be smaller, with corresponding descopes in science. It could be larger, with some impact on telescope stability and substantial impact on cost. Obscurations and segmentation are compatible with some of our options but not others; technology readiness of those options will drive our decision at least as much as obscurations and segmentation.

- Diffraction limited point spread function in a narrow FOV, roughly 1 sq. arcsec. Some options demand stringent optomechanical stability as well.[*]

Happily, the UV-optical community and the exoplanet science community are consonant in what they each consider a flagship-class mission.

The telescope size has implications for the available exoplanet options, but there is no firm association of starshades with larger telescopes, as Kasting suggested.[†] Segmentation and obscurations, which are a natural engineering response to larger sizes, do force us to drop consideration of some types of coronagraph instrument, and currently that affects the technology readiness picture.

6 Summary

Exoplanet science is compatible with UV-optical astrophysics in wavelength range, telescope size, wavefront quality, coatings, and operations/scheduling. We see this as an excellent opportunity to use one telescope to support both sets of science objectives.

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[*] J. Green, and S. Shaklan, Proc. SPIE 5170, D. R. Coulter, ed. (SPIE, San Diego, CA, 2003), pp. 25-37.
[†] http://science.nasa.gov/media/medialibrary/2011/07/21/7142011_ExoPAG_Report-Kasting.ppt

NASA ExoPAG Study Analysis Group #5: Flagship Exoplanet Imaging Mission Science Goals and Requirements Report

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Abstract

The NASA Exoplanet Program Analysis Group (ExoPAG) has undertaken an effort to define mission Level 1 requirements for exoplanet direct detection missions at a range of sizes. This report outlines the science goals and requirements for the next exoplanet flagship imaging and spectroscopy mission as determined by the flagship mission Study Analysis Group (SAG) of the NASA Exoplanet Program Analysis Group (ExoPAG). We expect that these goals and requirements will be used to evaluate specific architectures for a future flagship exoplanet imaging and spectroscopy mission, and we expect this effort to serve as a guide and template for similar goals and requirements for smaller missions, an effort that we expect will begin soon. These goals and requirements were discussed, determined, and documented over a 1 year period with contributions from approximately 60 volunteer exoplanet scientists, technologists, and engineers. Numerous teleconferences, emails, and several in-person meetings were conducted to progress on this task, resulting in creating and improving drafts of mission science goals and requirements. That work has been documented in this report as a set of science goals, more detailed objectives, and specific requirements with deliberate flow-down and linkage between each of these sets. The specific requirements have been developed in two categories: “Musts” are non-negotiable hard requirements, while “Discriminator” requirements assign value to performance in areas beyond the floor values set by the “Musts.” We believe that this framework and content will ensure that this report will be valuable when applied to future mission evaluation activities. We envision that any future exoplanet imaging flagship mission must also be capable of conducting a broad range of other observational astrophysics. We do not set requirements for this other science in this report but expect that this will be done by the NASA Cosmic Origins Program Analysis Group (COPAG).

1 Introduction

In February 2011 a single study analysis group (SAG) of the NASA Exoplanet Program Analysis Group (ExoPAG) was created to engage the scientific community in outlining the science goals and requirements for the next exoplanet flagship imaging and spectroscopy mission. By this time the Exoplanet Exploration Program had resolved that NASA should not continue to invest in infrared interferometry as a possible architecture for this mission.* Instead, single-aperture visible telescopes with internal coronagraphs or external starshades were judged to be the most viable candidate architectures. ExoPAG SAG #5 was tasked with defining the science goals and requirements for a flagship imaging mission in the 2020 decade in a way that was independent of specific mission

* Infrared interferometry is still considered a viable future technology for characterizing exoplanets. And the suite of atmospheric biomarker gases that might be detected at thermal-IR wavelengths is complementary to those in the visible/near-IR; and so ultimately any potentially habitable planet that is found should be studied in both wavelength ranges. But NASA and the ExoPAG community believe that a visible/near-IR direct imaging mission is probably easier and cheaper, and should be done first.

architectures, although, for example, we expect that a telescope aperture of at least 4 m will be required. The NASA astrophysics community also expects the next exoplanet flagship mission to serve as the flagship mission for NASA optical and UV astrophysics as suggested in the New Worlds, New Horizons Decadal Survey report. The ExoPAG and the Cosmic Origins Program Analysis Group (COPAG) have endorsed this notion, and the COPAG has agreed to develop the non-exoplanet requirements for this mission.

1.1 Scope of this Report

This document outlines the comprehensive science goals, more detailed objectives, and initial Level 1 science and mission requirements for the next NASA flagship exoplanet mission as determined by this exoplanet flagship SAG. The Science Goals are general statements of what science is intended to be achieved by this mission. These are made more specific in the derived list of Objectives, and then even more specific in the list of requirements. The Science Goals and Objectives can be considered Level 0 and 0.5 descriptions that define the Level 1 requirements.

The work done for this report exploits and builds upon the significant amount of work done over the past decade to define science goals, requirements, and mission architectures for future exoplanet imaging missions. We have particularly leveraged the Terrestrial Planet Finder-Coronagraph (TPF-C) Science and Technology Definition Team (STDT) report,[1] completed in 2006. The ExoPAG document “Points of Scientific Agreement” was drafted shortly after the January 2011 ExoPAG meeting and served as a starting point for defining what exoplanet characteristics should be characterized (atmospheric spectral features, orbit, mass). That document was also used to develop the highest level mission statement and scientific goals for this report.

We expect that a mission concept capable of achieving these goals – as well as significant other astrophysics ones – will be documented and presented to the 2020 Astronomy and Astrophysics Decadal Survey. There are no goals, objectives, or Level 1 requirements for any astrophysics fields beyond exoplanets included in this document; we expect that the COPAG will provide those at a later date.

1.2 Processes and People

Many people throughout the greater exoplanet science and technology communities contributed to the work in this report. Participants were invited to join at the January and June 2011 ExoPAG meetings and were also solicited by the Exoplanet Program office via email distribution in February 2011 and via the ExoPAG web site. We had preliminary discussions via email and one teleconference in May 2011 before deciding on an approach for the task at the June 2011 ExoPAG meeting in Alexandria, VA. There we decided to adopt a hierarchical set of science goals, science objectives, and requirements with clear flow-down and linkage between these elements.

We also decided then to adopt a two tiered Level 1 requirements structure, with a minimal set of firm requirements that must be met (“Musts” in our parlance) and a set of “Discriminator” requirements that assign value to improving performance beyond or outside of the Must requirement values. This structure was adopted to enable quantitative scoring of competing mission architectures (e.g., coronagraphs and starshades) using Kepner-Tregoe methods. [2] Eventually, weights will be assigned to Discriminators according to their scientific, technical, or programmatic importance. In the present work Musts and Discriminators were selected to be specific enough that they correspond to concrete figures of merit. We have identified Discriminators but did not assign weights to them, because the flagship mission is still far in the future; scientific and technical progress before its launch will change the scientific values of any weights and impact the feasibility of achieving desired performance.

The overarching aspiration, science goals, science objectives, and Must / Discriminator requirements of the mission were developed during and after the June 2011 ExoPAG meeting with much input and discussion from the community. We drafted an initial mission statement, science goals, and science objectives and posted them for discussion to our community discussion board, the ExoPAG Flagship Mission Requirements SAG Yahoo Group. Two teleconferences were held in the summer of 2011 where the members of the SAG commented and iterated upon these drafts. Nearly 60 people (see Table 1) ultimately joined this effort. We reached consensus on these components of the report by August 2011, and then we drafted and refined the Musts and Discriminator Requirements from September through December. We reported out on these efforts and the resulting body of work at the January 2012 ExoPAG meeting where this process and product was endorsed.

Table 1: List of SAG participants

Daniel	Apai	Jeremy	Kasdin	Jagmit	Sandhu
Jean-Charles	Augereau	James	Kasting	Gene	Serabyn
Rus	Belikov	John	Krist	Stuart	Shaklan
Jeff	Booth	Marie	Levine	Michael	Shao
Jim	Breckinridge	Chuck	Lillie	Erin	Smith
Kerri	Cahoy	Doug	Lisman	Arif	Solmaz
Webster	Cash	Carey	Lisse	Rémi	Soummer
Joseph	Catanzarite	Amy	Lo	Bill	Sparks
Supriya	Chakrabarti	Rick	Lyon	Karl	Stapelfeldt
Mark	Clampin	Avi	Mandell	Angelle	Tanner
Denis	Defrere	Joe	Marley	Domenick	Tenerelli
Michael	Devirian	Mark	Marley	Wesley	Traub
Tiffany	Glassman	Michael	McElwain	John	Trauger
Tom	Greene	Charley	Noecker	Zlatan	Tsvetanov
Olivier	Guyon	Pascal	Petit	Maggie	Turnbull
halleyguy		Joe	Pitman	Steve	Unwin
Sally	Heap	Marc	Postman	Robert	Vanderbei
Douglas	Hudgins	David	Redding	Amir	Vosteen
Lisa	Kaltenegger	Aki	Roberge	Darren	Williams

2 Science Goals

The primary scientific goal of the exoplanet flagship mission is detecting and spectroscopically characterizing at least one Earth-sized planet in the habitable zone of a nearby Sun-like star. We have also expressed this in a **Mission Statement** for a broad, non-specialist audience:

This mission will find potentially habitable planets and planetary systems orbiting nearby stars.

The mission's more specific **Science Goals** are:

Goal 1: Determine the overall architectures of a sample of nearby planetary systems. This includes determining the numbers, brightnesses, locations, and orbits of terrestrial to giant planets and characterizing exozodiacal dust structures in regions from habitable zones to ice lines and beyond. This information will also provide clues to the formation and evolution of these planetary systems.

Goal 2: Determine or constrain the atmospheric compositions of discovered planets, from giants down to terrestrial planets. Assess habitability of some terrestrial planets, including searching for spectral signatures of molecules and chemical disequilibrium consistent with the presence of life. Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.

Goal 3: Determining or constraining planetary radii and masses are stretch goals of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

3 Science Objectives

These **Science Goals** are now broken down into **Objectives** that serve as the basis for the mission's exoplanet systems requirements.

Objective 1: Directly detect terrestrial planets that exist within the habitable zones around nearby stars or, alternatively, observe a large enough sample of nearby systems to show with high confidence that terrestrial planets are not present.

Objective 2: Measure or constrain orbital parameters (semi-major axis and eccentricity) for as many discovered planets as possible, especially those that show evidence of habitability.

Objective 3: Obtain absolute photometry in at least three broad spectral bands for the majority of detected planets. This information can eventually be used, in conjunction with orbital distance and planet radius, to constrain planetary albedos.

Objective 4: Distinguish among different types of planets, and between planets and other objects, through relative motion and broadband measurements of planet color.

Objective 5: Determining or constraining planetary masses is highly desired but not required. Determining masses would allow estimates of planetary radii to be made, thereby enabling calculation of planetary albedos (Objective 3).

Objective 6: Characterize at least some detected terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. Distinguish between Jupiter-like and H_2O-dominated atmospheres of any super-Earth planets. Such information may provide evidence of habitability and even of life itself. Search for Rayleigh scattering to constrain surface pressure.

Objective 7: Directly detect giant planets of Neptune's size or larger and having Jupiter's albedo in systems searched for terrestrial planets. Giants should be detectable within the habitable zone and out to a radius of at least 3 times the outer habitable zone radius .

Objective 8: Characterize some detected giant planets spectroscopically, searching for the absorption features of CH_4 and H_2O. Distinguish between ice and gas giants, as well as between Jupiter-like and H_2O-dominated atmospheres of any mini-Neptune planets.

Objective 9: Measure the location, density, and extent of dust particles around nearby stars in order to identify planetesimal belts and understand delivery of volatiles to inner solar systems.

Objective 10: In dusty systems, detect and measure substructures within dusty debris that can be used to infer the presence of unseen planets.

Objective 11: Understand the time evolution of circumstellar disk properties around a wider star sample at greater distances, from early protoplanetary stages through mature main sequence debris disks.

The above Science Goals and Objectives are related as follows:

	Science Objectives										
Science Goals	1	2	3	4	5	6	7	8	9	10	11
1. Architectures	✓	✓		✓	✓		✓		✓	✓	✓
2. Compositions			✓	✓	(✓)	✓		✓			
3. Masses & radii			✓	✓	✓					✓	

Note that every row and column has at least one checkmark.

4 Level 1 Requirements

We have determined preliminary requirements from these objectives, but finalizing some requirements will require better knowledge than is currently available of the frequency of Earth-like planets ($\eta_{\oplus}$, called eta_Earth) and the amount and distribution of exozodiacal dust. That said, we next present the preliminary, provisional requirements based on our current assumptions for these values.

Since we are preparing to recommend a mission architecture from among several competing options, these requirements are posed in a form that serves the decision process but is different from the traditional structure (minimum/baseline/goal requirements). Specifically,

a. What we have traditionally called the minimum mission requirements—below which the mission has insufficient scientific merit and should be canceled—are herein called “Must” requirements.

b. In place of baseline and goal (stretch) mission requirements, we list a number of “Discriminators,” each of which is a criterion that represents added value in the science harvest.

If there is a minimum acceptable value of any Discriminator, it is included among the Musts; thus parallel language appears often in these two requirements sections. This decision process allows candidate missions to be compared on a variety of scientific, technical, and programmatic criteria even if they aren't comparable in cost and capability and have very different areas of excellence. The science-driven Musts and Discriminators are presented next.

5 Requirements

This list is primarily based on the TPF-C STDT requirements, translated into the new Musts/Discriminators form, which is described below. This form is preferred to a traditional requirements language because we will need to select a mission concept from among candidates with very different strengths and maybe cost. The present exercise should be viewed as a step in preparing for that complex decision. A traditional set of requirements has typically tended to bias the selection by emphasizing one criterion over others. A rough analogy is making an object that must fit inside a wooden box vs. one that fits inside a bag; the size of the bag allows comparisons between objects of very different shape and dimensions, without over-emphasizing the specific shape.

5.1 Assumptions and Definitions

On the whole we will stick with the definitions in Sec 1.2 of the STDT report. They are echoed here, in some cases with a slightly different flavor.

EID	Equivalent Insolation Distance; i.e. the distance between the star and planet for which the stellar irradiance is equal to that in our own solar system at a specified distance. For example, at 1 AU EID in the exoplanet system, the irradiance is the same as that here on Earth, even though the true distance is larger or smaller because of the star luminosity.
HZ	Habitable Zone, extends from 0.75-1.8 AU (EID)
IHZ	Inner HZ, extends from 0.7-1.0 AU (EID)
CumHZ	Cumulative partial Habitable Zones, the sum of the fraction of the HZ observed on each star during the mission. This excludes repeat observations of the same regions of orbital period, orientation, and phase.
CumIHZ	Cumulative partial INNER Habitable Zones, the sum of the fraction of the IHZ observed on each star over the entire mission. Note the distinction between the entire HZ and just the IHZ.
SMA	Semi-major axis, half the diameter of the long axis of an elliptical orbit.
TXP	Terrestrial eXoPlanet: defined as 0.8-2.2 R_{earth}, with SMA in the HZ, and eccentricity <0.2. We also adopt these assumptions: assume $dN/da \propto a$, and $dN/dM \propto 1/M$, uniform eccentricity distribution, with geometric albedo of 0.2 in the full science passband.
Candidate exoplanet	Point source in region of interest with appropriate brightness relative to the star.
Confirmed exoplanet	Shows common proper motion or recognizable high-res spectrum. Able to distinguish between planets and background confusion sources, and exozodiacal dust structures. Confusion can be broken using broadband colors, spatial resolution, spectra, or proper motion, whatever works most efficiently, high spatial resolution, spectra, possibly broadband colors or changing brightness with phase. Capability to thoroughly vet a leading candidate, not just keeping up efficiency by quickly eliminating false positives
Kuiper belt	Debris belt at >10 AU with surface brightness >24 mag/arcsec^2.
HZ exozodi	Exozodi surface brightness in habitable zone of 10× (TBR) that of a solar system twin at median inclination, with no asymmetries. LBTI observations are expected to reach this sensitivity,[3] so we should have statistically significant exozodi brightness data to this level. We assume every system is as bright as this measurement limit.

Confusion sources	Assume no confusion sources in the FOV. Discrimination from confusion sources is an important problem to address, but our knowledge is insufficient at this time.
IWA	Inner Working Angle. The minimum angular separation from the central star at which a faint point source has at least 50% throughput.
OWA	Outer Working Angle. The maximum angular separation from the central star at which detection of a faint point source requires an integration time no more than 4× (TBR) the value for an object of the same brightness at the optimal location within 0.5" of the star. For some star-suppression systems, the integration time rises sharply beyond some angular radius, the Nyquist angle given by the deformable mirror size.
δ-mag	The brightness ratio given in magnitudes between the central star and a faint point source that can be detected with high confidence. This can vary with angle from the star
SNR	Signal to noise ratio
FAP	False alarm probability, the probability that a point source that appears to be a planet would turn out to be something else.
“Detect” a planet	SNR compatible with FAPs of 1% (TBR). There should be a FAP for the planet search, another for confirmed exoplanets, and another for fully characterized exoplanets
TBR	To be revised
TBD	To be determined

5.2 Musts

The following are pass/fail bare minimum requirements for the mission to be considered worthy of the effort and expense. All candidate mission concepts must meet these criteria.

M1 Able to detect an Earth twin at quadrature in a Solar System twin at a distance of 10 pc
Rationale: “Pushpin” in the middle of the performance range required by M3. That is, any observatory able to meet M3 should naturally meet this as well.
Comment: Not a driving requirement, but helpful to communicate with NASA and taxpayers.
Maps to: O1

M2 Able to detect a Jupiter twin at quadrature in a Solar System twin at a distance of 10 pc
Rationale: “Pushpin” in the middle of the performance range required by M3.
Comment: Not a driving requirement, but helpful to communicate with NASA and taxpayers.
Maps to: O7

M3 Examine at least 14 CumHZs to detect point sources with TXP sensitivity
Rationale: Matches the STDT’s Requirement 3 for a minimum mission (§1.4.2), with optimistic $\eta_\oplus$=20%. We chose this case for the Musts, so that a less capable mission can still pass the Musts and be considered. This case also yields >95% probability of seeing at least one TXP assuming $\eta_\oplus$ =20%, and also offers a good chance of seeing several TXPs.
NB: the IWA and δ-mag needed to satisfy M3 are also sufficient to detect many giant planets outside the HZ.
Comment: If $\eta_\oplus$ =20%, the expected value of the number of TXPs detected is 2.8. The probability of seeing *at least one* TXP can be estimated by

$$P(1;\text{CumHZ}, \eta_\oplus) = 1 - P(0;\text{CumHZ}, \eta_\oplus) = 1-(1-\eta_\oplus)^{\text{CumHZ}} = 1-0.8^{14} = 95.6\%$$

Note that our “optimistic” $\eta_\oplus$ is supported by a preliminary analysis of the Kepler data[4], which argues for a value of more than 30%.

Maps to: O1, O7

M4 Examine at least 3 (TBR) CumIHZs to detect point sources with TXP sensitivity
Rationale: We want to ensure that not all of the partial HZs examined are in the outer HZ, 1-2 AU (EID). As with M3, this establishes capabilities that allow giant outer planet detection.
Comment: 3 was chosen semi-arbitrarily; this warrants more thought, and a capability assessment. At least we would like this number of CumIHZs to be naturally consistent with the capability of a mission that is sized to meet M3 above, assuming a reasonable distribution of SMA within the HZ.
Maps to: O1, O7

M5 Characterize every discovered candidate exoplanet by R>=4 spectroscopy (color photometry) across a passband from 0.5 µm to the maximum feasible wavelength less than 1.0 µm.
Rationale: Require instrumentation and time allocation to attempt this measurement on every planet found, large or small. Long wavelengths may be unreachable due to IWA or red leak.
Comment: Some are concerned that this "do whatever you can" language has no teeth. But others are concerned that alternative language will lead to impossible requirements.
Maps to: O3, O4, O8

M6 Able to characterize the "Earth" in a Solar System twin at 5 pc (TBR) and the "Jupiter" in a Solar System twin at 10 pc by R>70 spectroscopy across 0.5-1.0µm
Rationale: Require instrumentation and enough observing time for one such measurement. Assume favorable conditions in which IWA and brightness are not a limitation. The second clause about Jupiter connects a Must to O8, but we expect the mission to meet this easily.
Comment: Pushpin for hypothetical optimistic case. Not all found planets will be reachable by spectroscopy to 1.0µm because of IWA limitations; but if IWA scales with λ, then detection at 10 pc at λ=0.5µm is equivalent to 5 pc at λ=1.0µm. Similarly,

(10 pc) · (0.5µ) / (0.94µ) =	5.3 pc	H_2O
(10 pc) · (0.5µ) / (0.76µ) =	6.6 pc	O_2

The 10 pc distance chosen for Jupiter is fairly arbitrary, not challenging in photometry or IWA. Its purpose was just to make a requirement for outer giant planet spectroscopy. Also note that for some mission concepts, IWA is approximately independent of wavelength across a wide range.
Maps to: O6, O8

M7 Able to determine the orbital SMA to 10% for the "Earth" in a Solar System twin at 6.5 pc
Rationale: Like in STDT §1.4.2 (4)
Comment: Pushpin for hypothetical optimistic case. We declare that this knowledge has value, but our intent at this time is that IWA will not be the main challenge; it just requires instrumentation for star-planet angle measurements, and an adequate observing strategy. The 6.5 pc distance is fairly arbitrary in meeting that intent.
Maps to: O1, O2, O4

M8 Able to measure O_2 A-band equivalent width to 20% for the "Earth" at elongation in a Solar System twin at 6 pc.
Rationale: Establish measurement sensitivity to a key biomarker spectroscopic signature.

Comment: If IWA scales with λ, and the planet can be detected at 10 pc at λ=0.5μm, then it can be detected at 6 pc at λ=0.83μm, which is sufficient to span the O_2 A-band at λ=0.76μm.
Maps to: O6

M9 Able to measure H_2O equivalent width to 20% for the "Earth" at elongation in a Solar System twin at 5 pc and the CH_4 equivalent width in a "Jupiter" in a Solar System twin at 10 pc.
Rationale: Establish measurement sensitivity to a key biomarker spectroscopic signature. Was not included in STDT §1.4.2, but it could be assuming IWA scales proportional to λ.
Comment: If IWA scales with λ, and the planet can be detected at 10 pc at λ=0.5μm, then it can be detected at 5 pc at λ=1μm, which is sufficient to span the H_2O band at 0.94μm. Likewise, there is a strong CH_4 band at 0.889 μm, which we expect to be accessible at 0.5" working angle.
Maps to: O6, O8

M10 Conduct a search that has at least 85% (TBR) probability of finding at least one TXP and measuring its color at R=4 and measuring its SMA with 15% uncertainty (TBR) and measuring its spectrum (0.5-0.8μm)(TBR) with R≥70 and 20% (TBR) spectrophotometric uncertainty.
Rationale: The combination of several key measurements on one planet. This is full of TBRs, which will require a lengthy analysis to resolve; but it illustrates a tasty minimum likelihood of finding and coarsely-but-fully characterizing a TXP. This implicitly constrains search depth, time allocation, and characterization capability.
Comment: This is much more difficult than M3—being able to measure color, SMA, fine spectrum to 0.8μm, and 20% photometry **all on the same TXP.** If we don't scale back the parameters in this case, the observatory will be driven strongly by this requirement, and likely go well beyond the other requirements. We still don't know that a planet exists with characteristics that are favorable for all of these measurements together, so we can't assemble requirements that will get that one planet; but again we can substitute probabilities for the scientific unknowns ($\eta_\oplus$ and orbit/IWA), and then estimate the statistical likelihood of it for any mission concept.
Maps to: O1, O2, O3, O4, O6

M11 Absolute photometry of "Earth" at maximum elongation in a Solar System twin at 8 pc to 10%
Rationale: Like in STDT §1.4.2 (6), which refers to an Earth twin in a Solar System twin at 8 pc. Pushpin to fix a calibration requirement
Maps to: O3

M12 Able to guide on the central star as faint as V_{AB}=16 (TBR) for high contrast imaging at degraded sensitivity.
Rationale: Contrast for disk science is not as demanding as for TXP science, but generally demands a wider range of stars, often much fainter than TXP target stars.
Comment: We need further conversation with the SAG 1 team (characterization of exozodi disks). We hope this will also prompt a capability assessment. We are hoping for graceful degradation of coronagraphy with central star magnitude. A goal is sensitivity to mag 30 point sources in the neighborhood of a star of any magnitude.
Maps to: O9, O10, O11

M13 Capable of high-contrast optical imaging of extended structures with surface brightness sensitivity of (TBD of the star) at > TBD arcsec from the central star.
Rationale: Disk science
Comment: We need further conversation with the SAG 1 team (characterization of exozodi disks). Probably need a few such benchmarks on a curve.
Maps to: O9, O10, O11

N.B. there are no Musts for a number or percentage of *confirmed* exoplanets. Confirmation is a knotty problem, not well understood, and it may prove too big a challenge for the first mission we can afford. We would still get a list of exoplanet *candidates* and a significant scientific and technical step forward. See the mapping of Musts to Objectives at the end of the next section.

5.3 Discriminators

The following are Discriminators, which are not pass/fail but numerically scored based on quantitative or semi-quantitative metrics. The metrics are expected to be well-defined and unambiguous, like observatory mass, number of launch vehicles, number of science observations in 5 years, etc., and should be defined in a way that is applicable to all concepts.

The scores are rooted in those metrics and are ideally developed by consensus, but often fairly subjectively. Scores are a layer of abstraction from the metrics, to allow many Discriminators to be taken into consideration together, even though they may be of a dramatically different character. The set of Discriminators should be complete enough to allow each mission concept to accrue points for all of its strengths.

A set of weights are also developed by consensus, and reflect the relative importance of each Discriminator to the outcome of the mission. Each Discriminator has a numerical weight which applies to all concepts for that Discriminator. For each concept, a dot-product of the column of scores with these weights yields a single number, a composite score for the concept, which is the basis for choosing a mission concept. The scores and weights are both subjective, but we will conduct extensive tests of fiddling with these numbers to see how sensitive the final conclusion is to minor changes. If at the end we are comfortable that the decision rests on judgments that we all believe, we are ready to report a decision with confidence.

D1 Number of CumHZs searched to TXP sensitivity
Rationale: Beyond the minimum in M3, we want a deeper search (more CumHZs) to get more planets
Comment: An earlier version of this requirement specified a minimum δ-mag, but this was deemed redundant and overspecifying. We preferred staying close to (a) the probability of at least one planet and (b) the expected value of the number of planets.
Maps to: O1, O7

D2 Number of CumIHZs searched to TXP sensitivity
Rationale: Similarly, we want a deeper search of the IHZ; cf. M4 - more CumIHZs fills in the inner planets
Maps to: O1, O7

D3 Minimum brightness of exoplanet that is detectable at angles in the range from 1-2×IWA (TBR).
Rationale: Ability to see fainter point sources improves the depth of search (cf. M3, M4) and its completeness down to small sizes; also improves characterization by virtue of seeing more of the orbit. Typically δ-mag = 26, but larger δ-mag gets more planets.
Maps to: O1, O7

D4 Number of candidate exoplanets that are confirmed
Rationale: Establish the capability to do measurements to confirm candidate exoplanets.
Comment: See definition of "Confirmed." Confirming <u>every</u> exoplanet system could be very demanding for some mission concepts. Relaxing this number may leave many planet candidates unproven until a followup mission.
Maps to: O1, O7

D5 Number of discovered exoplanets characterized by R>4 spectroscopy (color photometry) across the full 0.5-1.0μm
Rationale: See M5. If there's any limitation or difficulty, it's better to characterize more planets by color.
Maps to: O3, O4, O8

D6 Number of discovered TXPs that can be characterized by R>70 spectroscopy across the full 0.5-1.0 μm
Rationale: See M6. It's better to characterize more planets for the presence of H_2O, e.g. by having a small IWA. These capabilities also aid the characterization of giant planets outside the HZ.
Comment: Again, this is a statistical estimate based on distributions and observing scenarios.
Maps to: O6, O8

D7 Number of discovered TXPs characterized by R>70 spectroscopy across 0.5-0.85 μm
Rationale: See M7. It's better to characterize more planets by O_2 even if H_2O is inaccessible. These capabilities also aid the characterization of giant planets outside the HZ, e.g. via methane at 728, 793, and 863nm, and water at 830 nm.
Comment: Again, statistical estimate based on distributions and observing scenarios.
Maps to: O6, O8

D8 Extended passbands to NIR and NUV
Rationale: Some mission concepts are capable of TXP sensitivity further into the IR or the UV. This can provide more atmospheric absorption bands and other information about the planet and exozodi.
Maps to: O6, O8

D9 Number (or percentage) of found candidate exoplanets for which we can test for common proper motion
Rationale: See D4 and the definition of "Confirmed." Common proper motion is the gold standard for proving the object is a true companion; some alternatives were listed above.

Comment: We don't know how many candidates will be detected, so we should not pin ourselves to a fixed *number*. And in an exoplanet-rich scenario, confirming a minimum *percentage* may be a challenge.
Maps to: O1, O7

D10 Number of found planets whose orbital SMA can be determined with ±10% uncertainty (TBR) or better.
Rationale: This may be difficult because of the number of visits required. This depends on agility for multiple revisits, confident detection each time, and accurate planet-star relative astrometry.
Comment: Perhaps also give credit for even finer SMA determination.
Maps to: O1, O2, O4

D11 Number of TXP masses determined to TBD%
Rationale: Measurement of the host star's astrometric wobble is the gold standard for exoplanet mass determination.[5] (Indirect methods have been proposed, but are vulnerable to scientific uncertainties.) No existing well-developed mission concepts are believed capable of providing this astrometric information, so there is no Must or minimum requirement for this knowledge. But if we can demonstrate convincingly that one or more concepts could provide this, we should give high scores for that.
Maps to: O4, O5

D12 Number of discovered TXPs characterized by absolute photometry
Rationale: See M10 – we want more planets characterized by absolute photometry
Comment: Again, statistical estimate based on distributions
Maps to: O3, O4

D13 Number of giant exoplanet candidates detected in ExoEarth target systems
Rationale: We want the capability to detect and characterize a variety of giant planets, especially to see if there are correlations between the presence and nature of TXPs and of giant planets. Also establishes the virtue of a large ratio OWA/IWA.
Maps to: O7, O8, O11

D14 Number of Kuiper Belts imaged in ExoEarth target systems
Rationale: Of course we want to detect many examples of inner and outer debris disks, but we especially want to see if there are correlations between the presence and nature of TXPs and of Kuiper Belts. Also establishes the virtue of a large ratio OWA/IWA.
Comment: We haven't defined "Kuiper Belt" by a range of characteristics.
Maps to: O9, O10, O11

5.4 Mapping of Musts and Discriminators to Objectives

Note that all rows in the following tables have at least one check mark. Also, all columns except O5 have at least one check mark in *each* table; O5 is captured in D11, and its absence from the Musts is explained in the rationale for D11.

	Science Objectives										
Musts	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M1: detect Earth twin	✓										
M2: detect Jupiter twin							✓				
M3: 14 CumHZs	✓						✓				
M4: 3 CumIHZs	✓						✓				
M5: colors			✓	✓				✓			
M6: fine spectra						✓		✓			
M7: orbital SMA	✓	✓		✓							
M8: oxygen						✓					
M9: water						✓		✓			
M10: all on 1 planet	✓	✓	✓	✓		✓					
M11: absol photometry			✓								
M12: guide on faint star									✓	✓	✓
M13: surface brightness									✓	✓	✓

Discriminators	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
D1: # CumHZs	✓						✓				
D2: # CumIHZs	✓						✓				
D3: max δ-mag	✓						✓				
D4: # confirmed	✓						✓				
D5: # planets, 4 color			✓	✓				✓			
D6: # planets, full spectra						✓		✓			
D7: # planets, part spectra						✓		✓			
D8: NIR and NUV						✓		✓			
D9: common PM	✓						✓				
D10: # orbit SMA	✓	✓		✓							
D11: # astrometric mass				✓	✓						
D12: # absol photometry			✓	✓							
D13: # giants w/ TXPs							✓	✓			✓
D14: # KuiperB w/ TXPs									✓	✓	✓

6 Conclusion

We believe this captures most of the features we value in a flagship mission concept, and prepares a process for selecting the best one. But of course, we expect modifications and additions to this list as our understanding improves.

More importantly, recent programmatic developments have motivated a look at how a smaller mission (1.5-2.5m telescope) might achieve some of these objectives in the near term, in lieu of a flagship which might take much longer. Indeed, a particular new 2.4m telescope opportunity seems like a possible path, but it would require great flexibility and compatibility with other astronomy objectives. This will make the selection of a planet-finding method even more exciting and more complicated at the same time.

Acknowledgments

We are grateful for Marie Levine's assistance in facilitating this effort and keeping momentum.

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Ultraviolet imaging of exoplanets

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1 Disclaimer

Direct exoplanet observations are nominally the province of the EXOPAG and are thus beyond the scope of this RFI. However, the authors feel that given the synergy between exoplanet observations in general, and direct ultraviolet imaging of exoplanets in particular, and ultraviolet astrophysics that this response is warranted.

2 Move to characterizing exoplanets

The study of extrasolar planets is one of the most exciting endeavors of modern science. The statistics are familiar and impressive. To date over 750 planets have discovered in about 600 planetary systems — and that is not counting the thousands of Kepler planet candidates awaiting confirmation.

The advent of high quality ultraviolet transiting observations (e.g. Vidal-Madjar et al., 2003, 2004; Linsky et al., 2010; Schlawin et al., 2010; Fossati et al., 2010; Sing et al., 2011) and possibly more, better, ultraviolet observations in the future (see France et al. response to this RFI) go a long way to furthering our understanding of the diverse properties of exoplanetary atmospheres. They have given us information about the composition, ionization, and dynamics (including the rates of atmospheric escape) of the atmospheres of a few planets.

Indeed, it is not at all surprising that ultraviolet spectroscopy has given us a large information return from the relative few observation which have been possible so far. Ultraviolet spectroscopy is central to our studies of planets in the solar system. It is a central tool in our studies of aurora on the Earth (Meier, 1991) and other planets (Feldman et al., 1993) and it reveals the similarities and differences of the interaction of the sun (both as an ultraviolet light source and as a particle source) with the upper atmospheres of the solar system planets (Clarke et al., 2005). Furthermore, since the emissions of solar system planets arise from electron impact and fluorescent sources, the emissions are not bounded by the star's

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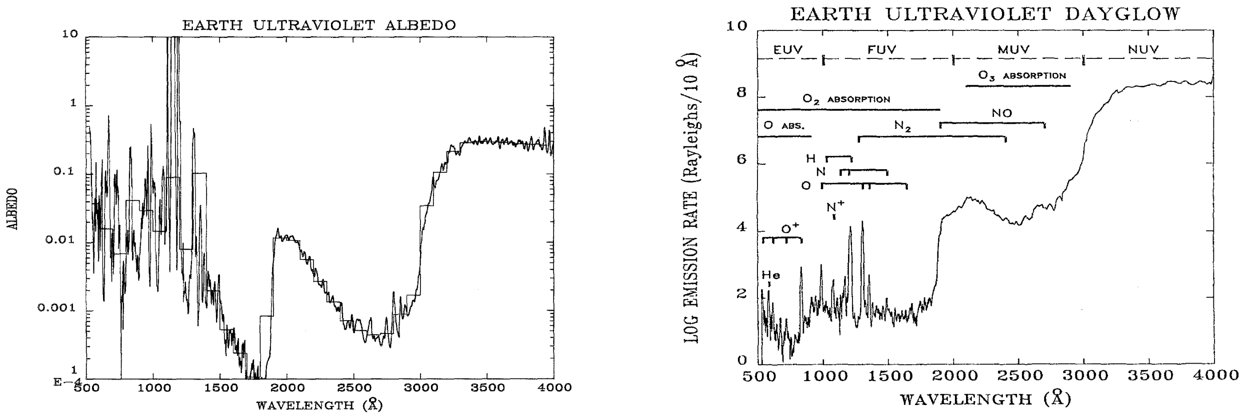

Figure 1: The spectrum and "albedo" of the Earth in the far ultraviolet is no lower than in the visible and, in select atomic and molecular transitions, can be higher than 1. This is because the far ultraviolet emissions arise from fluorescence and electron impact rather than thermal or scattering processes as they do in the infrared and visible. As a result the planet can emit more light than it receives from its host star at some wavelengths. Figures from Meier (1991).

intensity at the wavelength being observed - fluorescence will redistribute light from bright stellar lines to dimmer spectral regions and electron impact lines will appear in relatively faint stellar bands.

3 The need for imaging

Simple geometry heavily biases the systems which can be studied by transit methods to planets in close orbits. The search volume needed to find a transiting exoearth around a sunlike star at 1 AU will likely result in detections which are unsuitable to detailed follow up observations. The systems which are suited to transit spectroscopy are the extremophiles of planetary atmospheres; they will not tell us much about Earthlike or solar system like planets. In order to study planetary systems like the solar system in age, orbital configuration, and stellar type we are going to need to directly image systems which are not transiting.

This will have a profound impact on exoplanet science and our understanding of our place in the Galaxy. Astro2010 sees "Identification and characterization of nearby habitable exoplanets" as one of the "Science frontier discovery areas." This need, which is gradually being met, has been apparent from the earliest days of exoplanet observations. Soon after the first extrasolar planet was discovered, a group of scientists and engineers prepared a roadmap for the Exploration of Neighboring Planetary Systems (ExNPS). In their report they noted that *"Direct detection methods have to be sensitive enough to make high signal-to-noise detections of planets in just a few hours so that a large number of sources can be surveyed to a meaningful level, and so that crude spectroscopy can be carried out with the same apparatus to provide an initial characterization of the detected planets."* They further

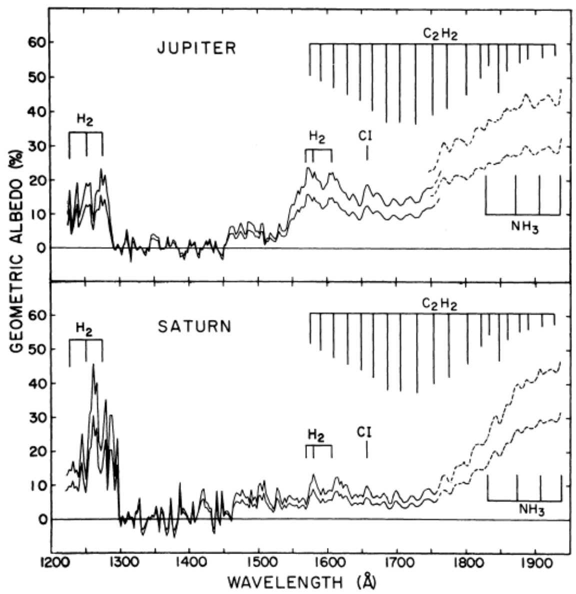

Figure 2: The "albedo" of the Jupiter and Saturn in the far ultraviolet. Like Earth, the "albedo" of the Earth in the far ultraviolet is no lower than in the visible and, in select atomic and molecular transitions at high resolution, can be higher than 1. Figure from Clarke et al. (1982).

stated "The goal of imaging a terrestrial planet is taken to mean making an image – a family portrait or an orrery – of the planet(s) in a planetary system around a nearby star and identifying whether any of these planets are habitable".

4 The need for ultraviolet imaging

Technology has advanced to the point where the first visible and near infrared images of such planetary system are being recorded (e.g. Kalas et al., 2008; Marois et al., 2008). Those first images are giving us information about the albedos and energy balance of extrasolar planets. However, much more will be learned from ultraviolet spectroscopy. The clouds on earth or the band structure of Jupiter can be seen in the visible and can tell us a lot about those objects but much more can be learned from the ultraviolet spectra of those bodies. The ultraviolet region contains the resonance lines of HI, OI, H_2, N_2, O_2, O_3, and many other important species (see figure 1). Ultraviolet coronagraphy would allow us to probe all of them.

5 Why ultraviolet imaging is possible

As usual with exoplanet research, the desirability of a particular observation is much more obvious than the achievability of that observation. In order to carry out UV exoplanet imaging one will need an ultraviolet coronagraph of combined with a spectrometer capable of recording spectra with enough resolution to "peak up" the ultraviolet emission lines under consideration. The spectrograph will also allow spectral differential imaging to improve the performance of the coronagraph. Such an instrument is beyond our current capability but the technologies which need to be improved are not fully mature so there is reason to believe that progress can be made.

5.1 Smaller telescopes

While it is clear that moving to the ultraviolet spectral region poses challenges beyond those already present with visible or near infrared coronagraphy it also brings some benefits. The canonical exoplanet mission (Levine et al., 2009) envisions a 4 meter class telescope with a coronagraph operating at 4 λ/d . By moving to the ultraviolet we will see an advantage of at least 3 and as much as 10 in this critical metric. This means that, with the same telescope and target, observations will be at 12 to 40 λ/d . On the other hand, the same diffraction limit could, in principle, be achieved with a telescope in the 0.5 to 1.5 meter range.

5.2 Tighter tolerances

To achieve this performance one will need to improve the optical figure of the coronagraphs and optical systems by a similar factor (3 to 10). While this is by no means trivial, there is reason to think that it is possible. Recent advances in adaptive optics have shown that wavefront control is possible at the 0.1 nm level on small scales (Trauger et al., 2011), and there seems to be no reason that is cannot be achieved at larger scales. Between the improved optical quality of EUV optics and rapidly improving adaptive optics the required optical performance should be achievable.

5.3 Fainter targets

In addition to the tighter tolerances UV observations of late stars will result in much fainter targets. The spectrum of the sun is approximately 10^6 times fainter in the ultraviolet than in the visible. With a 2.4 meter class telescope is will take an observation of approximately 5 days to observe a planet around even a fairly bright G star. It should be noted that this estimate may be somewhat pessimistic. France et al. (2010b) observed HD209458 and identified an emission feature at the orbital velocity of the planet *without a coronagraph*. France et al. (2010a) observations of J12073346-3932539 likewise may be detecting emission from that planet. The physics and planetary conditions of these observations are far from clear but they do give some indication that the observations may be easier than we are assuming here.

6 Science returned

The science return from such a program is considerable. In figure 3 we show that far ultraviolet imaging can distinguish between strong and weak magnetic fields. In figure 1 we present the ultraviolet spectrum of Earth, which shows strong absorption in the O_2 and

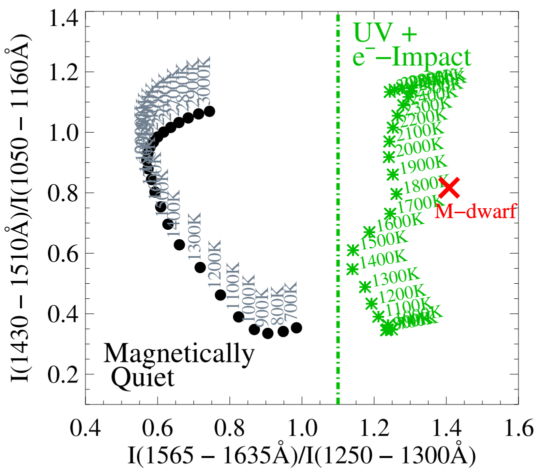

Figure 3: Far-ultraviolet "color-color" plots for gas giant planets with a range of surface temperatures. The plots are based on models of H_2 emission spectra in four narrow bands from 1050 - 1635 Å. These objects are readily separated by the presence/absence of electron-impact emission, which should depend strongly on the presence of a planetary magnetic field. Therefore, narrow-band far-UV imaging of exoplanets can provide constraints on the prevalence of planetary magnetic fields in extrasolar systems.

O_3 bands which are thought to be evidence of life. These are just two examples of the power of ultraviolet imaging of exoplanets.

7 What we need

In order to achieve these observations several technology improvements are required. We need wavefront control at the 0.1 nm level. We need high quantum efficiency ultraviolet detectors with very low dark noise. We *do not* need particularly large apertures.

While the technology improvements needed are significant, such a mission is achievable.

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From Protoplanetary Disks to Extrasolar Planets: Understanding the Life Cycle of Circumstellar Gas with Ultraviolet Spectroscopy

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1. Introduction

Few scientific discoveries have captured the public imagination like the explosion of exoplanetary science during the past two decades. This work has fundamentally changed our picture of Earth's place in the Universe and led NASA to make significant investments towards understanding the demographics of exoplanetary systems and the conditions that lead to their formation. The story of the formation and evolution of exoplanetary systems is essentially the story of the circumstellar gas and dust that are initially present in the protostellar environment; in order to understand the variety of planetary systems observed, we need to understand the life cycle of circumstellar gas from its initial conditions in protoplanetary disks to its endpoint as planets and their atmospheres. In this white paper response to NASA's Request for Information "*Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts (NNH12ZDA008L)*", we describe scientific programs that would use the unique capabilities of a future NASA ultraviolet (UV)/visible space observatory to make order-of-magnitude advances in our understanding of the life cycle of circumstellar gas.

UV radiation plays a critical role in the evolution of protoplanetary disks, the heating and evaporation of extrasolar planets, and directly probes the most abundant molecules in these environments. We outline four broad scientific investigations that address these topics using UV spectral observations. We first describe ***1)*** the importance of UV observations in understanding the production of biomarkers on potentially habitable, Earth-like planets, and ***2)*** the characterization of exoplanetary atmospheres, using spectroscopy to probe the compositions and thermodynamic structures of transiting planets. The Astro2010 Decadal Survey lists **"How do circumstellar disks evolve and form planetary systems?"** as a Frontier Science question for Cosmic Origins in the present decade (Blandford et al. 2010). We propose that this can be addressed with ***3)*** high-resolution UV molecular spectroscopy to measure the structure and composition of the disk and ***4)*** wide-field UV surveys of molecular emission that will allow statistical determination of protoplanetary gas disk lifetimes and the implications for the formation and evolution of exoplanetary systems.

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2. Characterization of Exoplanet Atmospheres: Terrestrial Worlds and Gas Giants

2.1 The Habitable Zone around Low-Mass Stars

The ultimate goal for exoplanetary science in the next two decades is the detection and characterization of habitable, Earth-like worlds. Stellar characterization is critical to interpreting these observations. An investment in stellar characterization is particularly important for low-mass stars (M- and K-dwarfs), which are perhaps the most promising targets for the detection of habitable planets (Segura et al. 2005; Rauer et al. 2011). For example, UV radiation is important to the photodissociation and photochemistry of H_2O and CO_2 in terrestrial planet atmospheres. The large far-UV/near-UV stellar flux ratio in the habitable zone around M-dwarfs can have a profound influence on the atmospheric oxygen chemistry on Earth-like planets. The strong far-UV flux may produce large, abiotic atmospheric abundances of O_2 through the dissociation of CO_2 (France et al. 2012). The O_2 production rate and the subsequent formation of O_3 are highly dependent on the spectral and temporal behavior of the far-UV (in particular, Lyα) and near-UV radiation field of the host star. Over 100 extrasolar planets (or planet candidates) orbiting M-dwarfs are known today, however only *three* of these systems have measured far- and near-UV spectra. At present, we cannot accurately predict the UV spectrum of an M-star; this lack of observational basis is hampering our ability to accurately predict the expected biosignatures from these worlds (Kaltenegger et al. 2011).

A spectroscopic survey of low-mass exoplanet host stars from 912 – 4000 Å will be able to characterize the spectral and temporal behavior of these systems, an essential input for atmospheric models of habitable zone planets. With *HST*, we can only observe the UV spectrum of an M-dwarf exoplanet host out to d ~ 10 pc with a reasonable investment in observing time (< 8 orbits), therefore if we want to determine the potential habitability of more than the nearest few Earth-like planets, a new observational capability is required. A future UV mission employing **moderate resolution (~10 km s^{-1}), low-background equivalent flux levels ($\leq 10^{-18}$ erg cm^{-2} s^{-1} $Å^{-1}$ in 10^4 sec), and photon-counting detectors ($\Delta t \leq 1$ sec)** would enable a survey of the known M-dwarf exoplanetary host stars within 50 pc (and K-dwarfs to > 200 pc), including all of the systems that can be studied in detail by *JWST*. The ultraviolet bandpass offers the best set of chromospheric, transition region, and coronal activity diagnostics in low-mass stars (the HI Lyman series, FeXVIII 974, CIII λ977, OVI λ1032, SiIII λ1206, OI λ1304, CII λ1335, FeXXI 1354, CIV λ1550, HeII 1640 Å, and MgII 2800 Å) that are critical to the characterization of the energetic radiation environment. This work is an essential investment towards our ability to reliably interpret biosignature molecules when they are discovered in the coming decades.

2.2 Transiting Planets

Short period planets are exposed to strong UV radiation fields from their host stars, and this energy deposition can inflate the planetary atmosphere. UV observations probe the extended upper atmospheres of the planets, providing unique access to the strong resonant transitions of the most abundant atomic constituents that can be observed in absorption during transit (e.g., H, O, C^+, Si^{2+}, and Mg^+ have been detected so far; Vidal-Madjar et al. 2003, 2004, Linsky et al. 2010, Fossati et al. 2010).

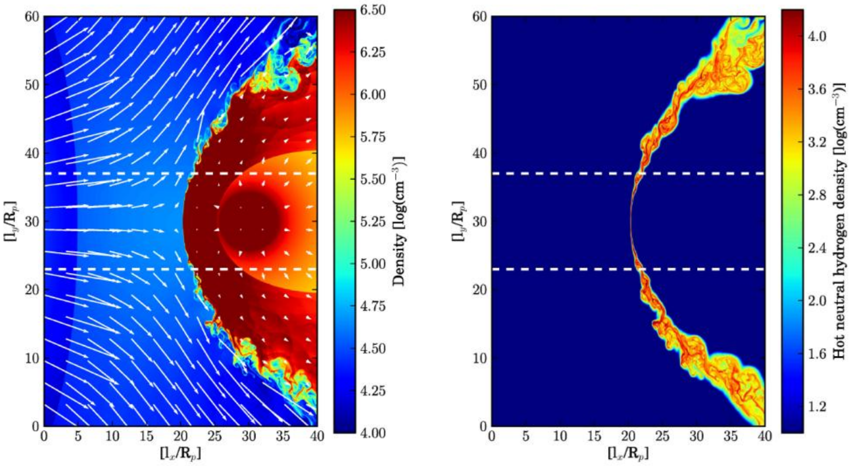

Figure 1: Hydrodynamic simulation of the interaction of stellar winds and the escaping neutral hydrogen atmosphere of a hot Jupiter (from Tremblin & Chiang 2012). UV transit observations provide a direct means to study the composition, structure, and evolution of exoplanetary atmospheres.

Together with models of the upper atmosphere, the observations can be used to study the ionization, chemistry, elemental abundances, thermal structures, and mass loss on transiting planets (e.g., Yelle 2004, Garcia Munoz 2007, Murray-Clay et al. 2009). Existing observations of close-in gas giant planets indicate that they are surrounded by thick envelopes of hot atomic hydrogen and ions that are created by photoionization and interaction with the stellar wind (see Figure 1 for an example). However, there are many competing interpretations of the observations (e.g., Vidal-Madjar et al. 2003, 2004, Ben-Jaffel and Hosseini 2010, Koskinen et al. 2010, Ekenback et al. 2010), and the combination of sensitivity and spectral resolution of the instruments aboard the *Hubble Space Telescope* are insufficient to resolve the differences between these interpretations. **Higher sensitivity ($\leq 10^{-17}$ erg cm^{-2} s^{-1} Å^{-1} in 10^4 sec) and resolution ($\Delta v < 3$ km s^{-1}) are required to study the dynamics of mass loss in extrasolar systems;** one of the primary motivations for future UV studies. Our current understanding of evaporating exoplanetary atmospheres are based on observations of *three planets*. Analogous to what we have learned from *Kepler*, when a statistical sample replaces a small number of easily observable targets, our fundamental understanding of exoplanetary atmospheres will almost certainly change. A future high sensitivity UV observatory is therefore necessary to carry out statistical surveys of transiting systems, including observations of planets orbiting lower mass stars, out to ~100 pc.

The primary constituent of gas giant atmospheres, molecular hydrogen (H_2), is best studied in the 912 – 1650 Å bandpass. H_2 lines are independent of the chromospheric variability that complicates UV transit studies of G, K, and M-stars; its narrow absorption lines will serve as excellent tracers of the temperature, molecular fraction, and velocity field of gas giant atmospheres. These lines could be detected in absorption against the bright CIII (977 Å), Lyβ (1026 Å), OVI (1032 Å), CIII (1175 Å), and Lyα (1216 Å) emission lines with high spectral resolution. The signatures of disintegrating rocky planets may also be observable against chromospheric metal lines (Rappaport et al. 2012).

In order to probe the details of atmospheric escape from "hot Jupiters", and eventually terrestrial mass planets, a new observational capability is required. Observations of Rayleigh scattering are the most direct means of determining the atmospheric scale height for both Jovian and terrestrial planets (Lecavelier des Etangs et al. 2008; Benneke & Seager 2012), an essential parameter for the interpretation of near- and mid-IR molecular transmission spectra from future (or proposed) NASA missions such as *FINESSE* and *JWST*. High-sensitivity, moderate spectral resolution **near-UV (1700 – 4000 Å) spectroscopy** would allow us to observe Rayleigh scattering of H_2, haze, and possibly CO_2 and N_2 atmospheres at the wavelengths where this mechanism has the largest observable signature (Sing et al. 2011).

3. The Structures, Compositions, and Lifetimes of Circumstellar Gas Disks

The lifetime, spatial distribution, and composition of gas and dust in the inner ∼ 10 AU of young (age ≤ 30 Myr) circumstellar disks are important components for understanding the formation and evolution of extrasolar planetary systems. The formation of giant planet cores and their accretion of gaseous envelopes occurs on timescales similar to the lifetimes of the disks around T Tauri and Herbig Ae/Be stars ($10^6 – 10^7$ yr). The formation of giant planet cores through the coagulation of dust grains (Hayashi et al. 1985) is thought to be complete on the 2 – 4 Myr dust disk clearing timescale (Hernández et al. 2007). However, recent results indicate that inner molecular disks can persist to ages ~10 Myr in Classical T Tauri Stars (CTTSs, Salyk et al. 2009; Ingleby et al. 2011a; France et al. 2012b), although these results are based on a small number of protoplanetary systems. Disk gas regulates planetary migration (Ward 1997; Armitage et al. 2002; Trilling et al. 2002) and therefore the migration timescale is sensitive to the specifics of the disk surface density distribution and dissipation timescale (Armitage 2007). Below, we describe two experiments that would observationally constrain the structures, compositions, and lifetimes of circumstellar gas disks; allowing us to better understand the formation and evolution of exoplanetary systems.

3.1 Measuring the Radial Structures and Elemental Abundances of Gas Disks

At the distances of typical star-forming regions (e.g., Taurus-Auriga or the Orion Nebula Cluster), 1 AU corresponds to an angular scale of < 0.01´´. ALMA is carrying out high-resolution molecular spectroscopy of protoplanetary disks, but is less sensitive to warm/hot gas at terrestrial planet-forming radii. Therefore, if one wishes to probe molecules in the region of terrestrial and giant planet-formation, UV and IR spectroscopy will be the technique of choice for the foreseeable future. UV spectroscopy is a unique tool for observing the inner molecular disk as **the strongest electronic band systems of H_2 and CO reside in the 1000 – 1700 Å bandpass** (Herczeg et al. 2002; France et al. 2011). We currently lack the combination of sensitivity and spectral resolution to measure the relative contributions of thermal, turbulent, and kinematic broadening of the molecular lines at planet-forming radii. **High-resolution (Δv < 3 km s^{-1}), high-throughput (≤ 10^{-17} erg cm^{-2} s^{-1} Å^{-1} in 10^4 sec)** spectroscopy would allow us to characterize the H_2 and CO profiles in unprecedented detail (Figure 2). This would permit the measurement of the radial gas profiles in rotating disks and the contribution from low-velocity disk winds (e.g., Pontoppidan et al. 2011) that may determine gas disk lifetimes. We emphasize that high-resolution UV spectroscopy will be the

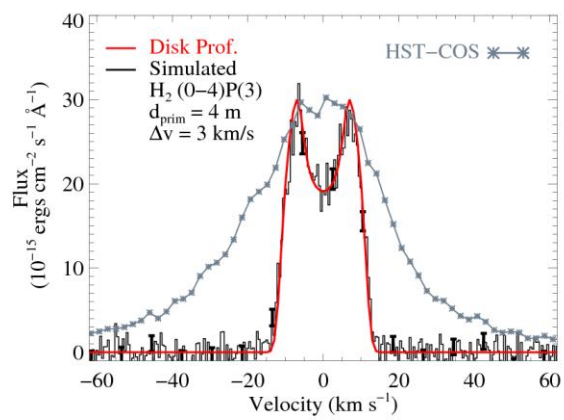

Figure 2: High-resolution (Δv = 3 km s^{-1}) H_2 line profiles can be modeled to constrain radial distribution of the molecular disk. A high-throughput echelle spectrograph enables detailed (S/N ≈ 20 in 3000 sec) mapping of the molecular disk from r ~ 0.1 – 10 AU for moderate inclination targets.

only means of resolving the structures of the H_2 disk; the highest resolution spectroscopic modes on *JWST* are limited to ($\Delta v \geq 100$ km s^{-1}), therefore UV observations will be critical for interpreting *JWST* observations of H_2, H_2O, and other molecules at terrestrial planet-forming radii.

UV observations of photoexcited CO and H_2 emission are also the best measure of the Lyα radiation field incident on the disk surface (Herczeg et al. 2004; Schindhelm et al. 2012). The complete Lyα emission line is not directly observable due to absorption and scattering in the intervening material, but constitutes ~80% of the total UV luminosity incident on the circumstellar environment and is essential for understanding protoplanetary disk chemistry at the epoch of planet-formation (Fogel et al. 2011).

The composition and physical state (e.g., temperature, turbulent velocity, ionization state) of a cross-section of the circumstellar environment can be probed using high-resolution absorption line spectroscopy of high-inclination ($i > 60°$) disks. **Spectral coverage in the 912 – 1150 Å bandpass is particularly important** for this work as the bulk of the warm/cold H_2 gas is only observable at $\lambda < 1120$ Å (via the Lyman and Werner (v' - 0) band systems). This work has only been possible on a small number of bright objects from protoplanetary (Roberge et al. 2001; France et al. 2012c) to debris (Roberge et al. 2000) disk systems. A systematic study of circumstellar disks across the 1 – 100 Myr timescale of giant and terrestrial planet formation holds great promise for understanding the evolution of the environments in which planets form.

3.2 The Lifetimes of Protoplanetary Gas Disks

Fluorescent H_2 spectra in the 912 – 1650 Å bandpass are sensitive to gas surface densities $\leq 10^{-6}$ g cm^{-2}, making these data an extremely useful probe of trace amounts of primordial circumstellar gas at $r < 10$ AU around pre-main sequence F – M stars. In cases where mid-IR CO spectra or traditional accretion diagnostics (e.g., Hα equivalent widths) suggest that the inner gas disk has dissipated, far-UV H_2 observations offer unambiguous evidence for the presence of a molecular disk (Ingleby et al. 2011b; France et al. 2012b). There is growing evidence that gas-rich disks can persist to several times the 2 – 4 Myr dust dissipation timescale (Figure 3), however this work has been limited by small sample sizes in the UV spectroscopic surveys ($<10^2$) compared to the dust SEDs compiled from mid-IR photometry and spectroscopy ($>10^4$; each square in Figure 3 represents 10s - 100s of stars). Uniform spectral surveys of entire local star-forming regions are required for a systematic determination of the gas disk lifetimes and therefore the timescales for gas envelope

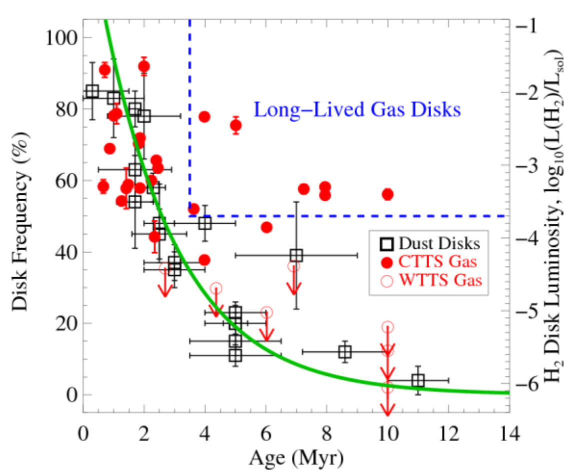

Figure 3: Far-UV H_2 emission lines are a sensitive measure of the molecular disk surface. Dust disk dissipation has a characteristic timescale of 2 – 4 Myr (open squares, adapted from Wyatt 2008), while a growing number of gas-rich disks are observed to persist to ≈ 4 - 10 Myr (filled red circles; France et al. 2012b).

accretion and migration of planetary cores through their natal disks.

A far-UV survey of H_2 and CO disks naturally lends itself to a **multi-object spectrograph (MOS, 10′ × 10′ field-of-view)** approach and is a strong science driver for the development of such an instrument for a future mission. **Moderate spectral resolution ($\Delta v \approx$ 100 km s^{-1}, at $F_{\lambda} \leq 10^{-16}$ erg cm^{-2} s^{-1} Å^{-1} in 10^3 sec)** is sufficient to separate blended H_2 emission lines for robust spectral identification and flux measurement. By studying a range of star-forming regions, from ~ 1 Myr (e.g., the Orion Nebula Cluster) to ~30 Myr (e.g., the Tucana/Horologium Association), we can not only statistically characterize the gas disk lifetimes, but also constrain the evolution of the UV radiation field (from accretion-dominated to chromosphere-dominated) incident on the terrestrial and giant planet formation regions during the growth of planetary cores and atmospheres. Combining this far-UV spectral survey with roughly contemporaneous near-UV (1700 – 4000 Å) multi-band imaging or low-resolution spectroscopy would enable the measurement of robust mass accretion rates. Comparing the mass accretion rates with the disk lifetimes will allow us to better understand the physical processes that govern the dissipation of primordial protoplanetary disks and the transition to gas-poor debris disk systems.

4. Summary

We have given four sample investigations where a future NASA mission with a UV spectroscopic capability would provide fundamentally new insight into how exoplanetary systems form and the physics that governs their atmospheres. **We argue that high-sensitivity and low background equivalent fluxes are a requirement for this mission.** Advances in component technology such as high-reflectivity UV coatings (Beasley et al. 2012; factor of 3 improvement per optic at $\lambda < 1100$Å) and low-noise borosilicate glass photon-counting detectors (Siegmund et al. 2011; factor of ~10 lower noise than *HST*-COS detectors) will provide many of the advantages of a large telescope for a fraction of the cost. We suggest that including both a high-resolution point source spectrograph and a MOS operating at lower resolution will provide the largest grasp in observatory discovery space for exoplanet and related research. Technology investment in low-scatter echelle UV spectrographs (e.g., France et al. 2012d; factor of up to ~100 improvement in scattered light control at $R > 10^5$) would provide a means for achieving the order-of-magnitude gains necessary to carry out the science without the commensurate increase in telescope diameter. We would be happy to present a summary of this report at a workshop on future UV/visible science drivers.

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SOLAR SYSTEM SCIENCE OBJECTIVES WITH THE NEXT UV/OPTICAL SPACE OBSERVATORY.

NASA Cosmic Origins Program Request for Information: Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts. White Paper to be submitted by 10 August 2012.

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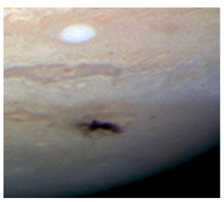
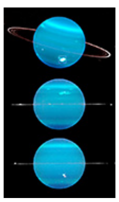

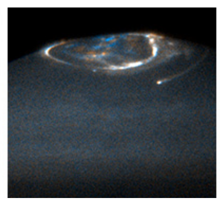
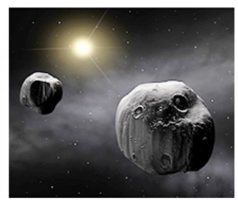
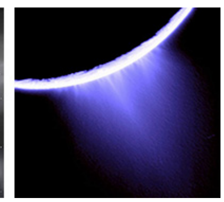

Summary

NASA's Great Observatories (and smaller space telescopes) enable a wide range of solar system science investigations, particularly in the ultraviolet, optical, and infrared ranges. These investigations are an important part of the Cosmic Origins program, providing a local reference point for the origin and evolution of stars and planetary systems. ***The next UV/optical space observatory can drive fresh insights into the origin and evolution of the solar system, if the technical requirements for planetary observations are met. These requirements are easily achieved via the groundwork that has already been done for HST and JWST.***

Some relevant research topics can be identified, although a strength of space observatories is that they can make observations to solve questions that have yet to be raised. Auroral emissions in atmospheres and magnetospheres of the giant planets can be effectively sensed only by space-based UV instruments. Observations of auroral phenomena tell us about the exchange of energy, mass, and momentum in magnetized plasmas—our closest analog for the inner portions of planet-forming disks around active protostars. These observations form a bridge between solar system planets and exoplanets. The compositional diversity of surfaces and atmospheres of planets and their satellites can also be characterized, illuminating both past and present solar system conditions. The dynamics of outer planet atmospheres can be studied by mapping jets, waves, vortices, storms, and impact debris fields at high spatial resolution. Atmospheric dynamics constrain the internal heat release and thermal evolution of gas giants, whose early analogs include glowing objects directly imaged around other host stars. One important point is that time-domain science is critically important to the rapidly changing planetary objects. Planetary observations with HST remain a vital part of the HST scientific program more than 20 years post-launch.

The proximity of solar system targets enables investigation at a high level of detail, but unique technical challenges result. The next UV/O space observatory must be able to observe bright targets, requiring a large dynamic range if faint object sensitivity is a driver for other science goals. The capability to track moving targets is also essential, although HST has shown that linear tracking (included in all 3-axis stabilized platforms) is sufficient to do great science. Although high spatial resolution is beneficial to solar system science, it cannot come at the expense of angular coverage, as solar system objects can span a field of view up to an arcminute. Placement of the observatory at a Lagrange point or in high Earth orbit eliminates limitations on temporal sampling and duration that interfere with time-domain solar system observations done from HST or the ground, and greatly decreases the geocoronal UV background emissions. When planning a future UV/O telescopic mission, a comparison with ground-based capabilities is often made. It is important to keep in mind the significance of the stable point spread function (PSF) and overall response of a telescope in space compared with ground-base AO systems. After new Plutoids are discovered, and imaged using AO on the Keck 10 m telescope, the 2.4 m HST is then employed to learn the true shape and size of the object – the justification is the stable PSF.

Scientific Investigations

In this white paper, we give a representative selection of solar system investigations that would be enabled by a UV/O space telescope, with the objective of defining common science requirements. Time domain science—either the direct study of variable phenomena, or the use of variable phenomena to understand the planets themselves—often requires the use of space telescopes due to their photometric stability and relaxed timing constraints.

The Discovery program's scope should be broadened to include planetary science from space based telescopes, according to the planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (SSB, 2011). Many time-domain solar system studies require higher spatial or spectral resolution than can likely be provided by a planetary telescope within the Discovery cost cap (Wong et al. 2009a, Content 2009). However, a facility class UV/O observatory, on the other hand, would enable much of this original science (see Table 1).

Table 1. Examples of solar system science investigations that can be explored with a UV/O space observatory. Note that since most investigations requiring spectroscopic data also require spatially resolved spectra, an integral field spectrometer is a appropriate spectroscopic instrument choice. Wavelength regimes are ultraviolet (UV), optical (O), and near infrared (IR).

Investigation	Category	Data type (wavelength regime)	Sampling scales	Campaign duration	Resolution: R = spectral, θ = spatial
Giant planet zonal winds and vortices	Atmospheres	Imaging (O)	Hours, single target rotation period	Years	$\theta \le 0.05''$
Cloud/storm evolution and variability	Atmospheres	Imaging, spectroscopy (O, IR)	Hours, days	Days, years	$R \ge 2500$ $\theta \le 0.05''$
Occultations	Atmospheres	Photometry, spectroscopy (UV, O, IR)	Milliseconds	Hours	$R \ge 100$–1000

Aurorae, magnetospheres	Atmospheres/ space science	Imaging, spectroscopy (UV)	Minutes, hours	Years, hours	R ≥ 500 θ ≤ 0.05"
Volcanic trace gases	Atmospheres/ geology/ astrobiology	Spectroscopy, imaging (UV, O, IR)	Days	Years	R ≥ 500–10000
Volcanic plumes	Geology	Imaging, spectroscopy (O, IR)	Days, hours	Years	R ≥ 2500 θ≤0.025"
Cryovolcanism	Geology/ astrobiology	Imaging, spectroscopy (UV, O, IR)	Days	Years	R ≥ 2500 θ≤0.025"
Mutual events, lightcurves	Small bodies	Photometry (O)	Milliseconds, minutes	Hours, months	R ≥ 5 θ > 10"
Cometary evolution	Small bodies	Imaging, spectroscopy (UV, O, IR)	Hours	Days	R ≥ 5 θ ≤ 0.05"

Wind velocities: Cloud-tracking studies illuminate the 3-dimensional wind fields in giant planet atmospheres as well as flows within coherent vortices like the Great Red Spot on Jupiter. These cloud-level velocities are the main constraints for studies in atmospheric dynamics. Sampling scales that include image pairs separated both by hours and by a single planetary rotation period provide the most accurate velocities (Asay-Davis et al. 2009). Measurements separated by one target rotation period, which for the giant planets is typically longer than a single terrestrial observing night, cannot be taken from a single ground-based observatory. Observation campaigns on the order of a decade reveal fundamental changes such as shifts in Saturn's haze distribution and equatorial wind speeds (Porco et al. 2005) and the shrinking of the potential vorticity anomaly associated with Jupiter's Great Red Spot (Asay-Davis et al. 2009). Cloud-tracked Martian winds constrain general circulation models (Kaydash et al. 2006). Existing data sets have large temporal gaps because space telescopes are based on single epoch observations constrained by observing cycles rather than by scientifically-determined campaign durations.

Cloud and storm evolution: The formation and evolution of clouds and storms is central to the topic of energy transport in planetary atmospheres. For example, Mars Global Surveyor observed dust storm 2001a with high temporal resolution, providing new insights into the origin and evolution of dust storms and new constraints on global circulation models for Mars (Smith et al. 2002, Strausberg et al. 2005). In the outer solar system, New Horizons spectroscopic imaging data spanning five Jovian rotations charted the evolution of an ammonia cloud system, providing a crucial piece of the puzzle of the scarcity of such signatures in a cloud layer that is supposedly dominated by ammonia ice (Reuter et al. 2007). Similar studies with a baseline long enough to determine statistical trends would inform questions such as the transport of internal heat through convective storms (Ingersoll et al. 2000) and the pattern of belt-zone transport and wave dynamics (Showman and de Pater 2005, Simon-Miller et al. 2012). Serendipity, rather than desired temporal sampling, allowed Sánchez-Lavega et al. (2008) to observe the genesis of powerful convective plumes at 23° N in Jupiter's atmosphere; these plumes were part of a poorly understood global upheaval and are associated with long-term changes in the upper tropospheric haze distribution (Wong et al. 2009b). Clouds on Titan show intriguing variability (Schaller et al. 2006) but high-resolution observations have been available for only a fraction of a Titanian season; a facility UV/O observatory would enable a long campaign duration optimized to capture seasonal variation and link it to a methane cycle analogous to the Earth's hydrologic cycle. Aerosol distributions on Uranus and Neptune vary on diurnal to seasonal timescales, tracing the causes and effects of very different solar forcing and internal heat release on these otherwise similar planets (Sromovsky et al. 2003, Rages et al. 2004, Hammel and Lockwood 2007, Sromovsky et al. 2007).

Occultations: The density, thermal, and compositional profiles of planetary atmospheres are probed with high vertical resolution using optical and ultraviolet stellar occultations (Atreya 1986, Smith and Hunten 1990). Tenuous atmospheres can be discovered using this technique; this was how Pluto's atmosphere was unambiguously identified (Elliot et al. 1989). With vertical resolution tied directly to sampling rate, occultations drive high-frequency sampling requirements. Space-based occultation experiments have the advantages of photometric stability and access to the ultraviolet region of the spectrum, where spectroscopic occultation observations return compositional profiles.

Aurorae and magnetospheres: Auroral and airglow emission has been observed on Jupiter, Saturn, Uranus, Io, Europa, and Ganymede. The dynamics of auroral spectral and brightness distributions reveals magnetospheric interactions with the solar wind and with planetary satellites. Observations from space can track the emission, which is variable on time scales of less than an hour and can vary with seasonal timescales that are decades long for the outer planets (e.g., Clarke et al. 2009). Exoplanets may emit cyclotron radiation that can be detected in the near future (Vidotto et al. 2010), and validating models of these distant systems requires testing against observations of magnetospheres in our solar system.

Volcanism and cryovolcanism: Volcanic processes are either known or plausible on several rocky and icy solar system bodies. Active volcanism on Io was discovered when Voyager imaged a plume over the volcano Pele (Morabito et al. 1979), a structure that easily could be resolved by a 4-m class UV/O space telescope with a 400-nm diffraction-limited resolution of about 80 km at a typical geocentric distance. Ultraviolet stellar occultations confirmed the spatially-confined cryovolcanic plumes in the south polar region of Enceladus (Hansen et al. 2006) and would be enabled by stellar UV occultations of other icy bodies. A search could be conducted for new cryovolcanic sources in the outer solar system on satellites and Kuiper belt objects, with a high-risk long term monitoring program. On Venus, a variable concentration of SO_2 at the cloud tops measured via ultraviolet spectroscopy hints at potential volcanic activity, and a space observatory could continue with both this technique as well as with searches for corresponding variation in the deep atmospheric SO_2 concentration, and for direct detection of thermal radiation from lava flows (Esposito 1984, Bézard et al. 1993, Hashimoto and Imamura 2001). Spatial and temporal variation of Martian CH_4 has recently been claimed, requiring either a geochemical or astrobiological origin to replenish the gas against photochemical destruction (Formisano et al. 2004, Krasnopolsky et al. 2004, Mumma et al. 2009). The variability of Martian methane has not been well constrained and will help to determine the source of the gas.

Small body time-domain photometry and astrometry: Dwarf planets and small solar system bodies reveal basic physical characteristics both in photometric light curves that are modulated by rotation and by changing viewing geometry, and in astrometric image sequences of multiple systems. Mutual events such as eclipses and occultations also contribute. Basic information gained from these studies will include sizes, shapes, albedos and albedo patterns, and masses and densities of multiple systems. Ground-based programs using moderate aperture telescopes have contributed greatly to this area, but fainter targets require larger telescope apertures that are limited by oversubscription. Resolving multiple systems requires them again to be bright enough to enable adaptive optics observations from the ground, whereas a UV/O space observatory would be able to resolve fainter and smaller targets, enhancing statistics on binarity rate and other properties in the populations of small bodies in orbit around the Sun.

Small body population studies: Small solar system body populations clearly provide clues to the formation and evolution of our planetary system. But they also serve as parent bodies for debris disks similar to those around other stars, where parent bodies are far too small to be directly observed. UV/O space observatories like Hubble and its successor play important roles in the studies of these populations. The UV colors of populations with different collisional histories (and thus surface ages) reveal the effects of space weathering, and only high-resolution space imaging can reveal faint binaries and companions, since adaptive optics are limited to targets bright enough to enable wavefront sensing.

Cometary evolution: Shoemaker-Levy 9 and subsequent disrupting comets provided spectacular opportunities for sequential imaging to reconstruct the comet's fragmentation history, density, and internal structure, and to study the diversity of internal structure, surface layering, and chemistry among cometary nuclei (Asphaug and Benz 1994, Solem 1994, Sekanina et al. 1998, Boehnhardt 2002, Kidger 2002). These comet properties also control atmospheric entry fragmentation, a key consideration for the determination of surface ages by crater-counting (Korycansky and Zahnle 2005). Accurate fragment trajectories allow measurements of competing influences such as rotation, solar radiation pressure, outgassing, and clumping. Identifying fragments and their trajectories requires sampling frequencies on the order of hours and campaign durations of at least several days. Gas production can increase dramatically during fragmentation (Crovisier et al. 1996), allowing infrared spectroscopic observations to constrain compositional heterogeneity in the parent bodies (DiSanti and Mumma 2008).

Scienctific Requirements

Moving target tracking: Solar system targets are not fixed with respect to the stars. Linear tracking approximations to the target motion have worked well for HST, and the software system to support this is in place and working. All 3-axis stabilized spacecraft are designed with linear tracking capability to move from place to place on the sky, so the inclusion of moving target tracking is neither expensive nor a new development effort.

Bright objects: High sensitivity drives the requirements for faint object investigations, but many solar system investigations require the capability to observe bright targets.

Angular resolution: Studies of planetary dynamics require the resolution of small distant objects such as cloud features, volcanic plumes, and binary objects with small separations. With a nominal 4-m aperture, the new UV/O facility would achieve an angular resolution of about 25 mas at 400 nm. This resolution is comparable to that provided by HST and the best current ground-based telescopes, which have demonstrated a wealth of time-domain science opportunities. In the coming decades, extremely high resolution will be afforded by large ground-based telescopes with adaptive optics, but solar system observations with these facilities can only be done at rare intervals and for short durations. The stable PSF, sensitivity, and spectral response achieved in space have all proven to be invaluable on HST, and a smaller aperture in space has great merit compared with the new generation of large ground-based systems.

Sampling interval: Critical sampling intervals for various programs typically range from hours to days. Occultation light curves will push the short-interval limits with millisecond-range sampling intervals. The full range of optimal sampling intervals will be enabled by an observatory located in high Earth orbit, at an Earth-Moon or Earth-Sun Lagrange point, or in a Spitzer-esque breakaway orbit, rather than in low Earth orbit, where observations would be interrupted by frequent and/or long Earth occultations.

Campaign duration: Campaigns lasting the full mission lifetime will enable both high-return/high-risk science such as cryovolcanic activity surveys, as well as studies of seasonal variations on objects in the outer solar system.

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Science Drivers for a Wide-Field, High-Resolution Imaging Space Telescope Operating at UV/Blue Optical Wavelengths[1]

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I. Summary

A wide-field (0.5-1 deg^2), ~1m-class space telescope that provides nearly diffraction-limited imaging (FWHM ~ 0.15″) at UV/blue optical wavelengths (0.15–0.55 μm) has the potential to make a unique, powerful, and lasting contribution to modern astrophysics. Such a mission would be a natural successor to both the Hubble Space Telescope (HST) and the Galaxy Evolution Explorer (GALEX), and would far surpass any ground-based optical telescope in terms of angular resolution. It would also provide crucial "UV/blue" imaging to supplement longer-wavelength data from future dark energy space missions (Euclid, WFIRST) as well as from the ground-based Large Synoptic Survey Telescope (LSST). For maximum scientific impact and complementarity with Euclid/WFIRST, the facility should allow the implementation of GO/PI programs, but concentrate initially on a small number of "legacy" surveys — including a "wide survey" that would cover an area of at least ≈5000 deg^2, in three filters, to depths of ≈ 25.8 mag (UV), 27.1 (u) and 27.8 (g). We review the rich and diverse science investigations that such a wield-field imaging facility would enable, which include (but are not limited to) dark energy, galaxy evolution, near-field cosmology, stellar astrophysics, the outer solar system, and time-domain astronomy.

II. Scientific Context

Perhaps no astronomical facility in history has had a greater impact than the Hubble Space Telescope (HST), which is widely regarded by scientists and the public alike as an unconditional success. However, HST will almost certainly cease operations before the end of this decade, either due to orbit decay or failure of a critical subsystem, and astronomers worldwide will then lose access to the high-resolution, UV/optical/IR imaging capabilities that they have come to rely on for more than two decades. Those capabilities have so profoundly changed the scientific landscape that much of our current understanding of astrophysics can be traced directly to HST. Meanwhile, GALEX — the highly successful SMEX mission that was launched in 2003 and went on to pioneer the field of panoramic UV imaging — is also likely to cease operations soon. It is expected that the launch of Astrosat in ~2014 will provide wide-field UV imaging capabilities, for a five-year period, but not at high resolution (i.e., FWHM ~ 1.8″).

Future (i.e., post ~2020) space imaging missions are instead concentrating on the IR/red-optical spectral region (i.e., ~0.55 to 2μm) driven by the desire to better understand dark energy: i.e., both Euclid and WFIRST aim to perform IR/red-optical imaging surveys of 15,000-20,000 deg^2. However, optical data remains essential for the success of these missions. For instance, according to current plans, IR/red-optical data from the first of these missions (Euclid, which is scheduled for launch in 2019) will be combined with ground-based (optical) imaging from the Large Synoptic Survey Telescope (LSST) to measure the dark energy equation of state.

Beyond this critical contribution to dark energy studies, LSST is expected to be a powerful research tool with many scientific applications. Nevertheless, some of the most pressing questions in astrophysics and cosmology can be addressed only through short-wavelength (i.e., ≈0.15

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to 0.55μm) imaging from space, which offers a number of key advantages over ground-based observations: i.e., much better image quality and stability, higher observing efficiency, lower sky backgrounds, superior photometric precision, and access to critical spectral regions, such the UV, that are unobservable from the ground.

In our view, a wide-field, high-resolution imaging capability at UV/blue-optical wavelengths represents the single most important "unfilled niche" among the international suite of astronomical facilities that are expected to be in operation near the end of this decade. The science drivers for a for such a facility have recently been examined as part of a concept study sponsored by the Canadian Space Agency for a wide-field, high-resolution imaging space telescope, as recommended in the recent *Long Range Plan for Canadian Astronomy* (Pritchet et al. 2011). The present document is based largely on lessons learned during the CSA concept study (Côté al. 2012).

III. Technical Requirements and Implementation Strategy

Wide-field imaging is the backbone of astrophysics. While many ground-based optical telescopes are equipped with mosaic CCD cameras, a vast array science drivers (see §IV) require the combination of *wide field of view* with *exceptional imaging quality* in the UV/blue-optical region — requirements that cannot be achieved from the ground. Although it is not the purpose of this document to advocate a specific mission concept, the technical requirements needed to address the science questions listed below have already been examined as part of our CSA study. We therefore briefly summarize the "baseline" technical requirements that are needed to achieve the key science goals, as well as possible strategies for mission operations.

The baseline specifications adopted in the discussion of science drivers (§IV) is a 1m, unobscured aperture telescope that carries out imaging over a 0.67 deg^2 field in three broad filters in the UV/blue-optical region: (1) 0.15-0.32μm (the 'UV' filter); (2) 0.32-0.41μm (u); and (3) 0.41-0.55μm (g). Imaging quality is nearly diffraction limited in each band, with FWHM ~ 0.15″. Baselined to a five-year mission lifetime, the facility would focus on 3-4 "Legacy" surveys during its first 2-3 years of operation, and then move on to the implementation of routine GO/PI programs. The largest of the Legacy surveys — denoted below as the Wide Survey — would perform UV-, u- and g-band imaging to depths of ~25.8, 27.1, 27.8 mag, respectively, over a minimum area of 5000 deg^2 that overlaps with the Euclid and LSST survey footprints.

IV. Science Drivers

We describe briefly a number of scientific investigations that would be enabled by a facility of the sort described above. While this list is far from complete, the programs are representative in that they illustrate the breadth of science that can be addressed using wide-field, high-resolution imaging in the UV/blue-optical spectral region. We include several examples of how high-resolution, UV/blue-optical imaging could leverage the longer-wavelength data from forthcoming dark energy missions, thereby enabling science that would not be possible with either mission alone. While the discussion in such cases focuses mainly on Euclid, given its somewhat more mature status compared to WFIRST, many of the same arguments apply to the latter mission.

1. Cosmology and Dark Energy

Photometric Redshift Measurements: ESA's Euclid mission aims to measure of the geometry of the universe through baryon acoustic oscillations (BAO) and weak lensing (WL). For the WL analysis, shape measurements for galaxies — carried out in a broad red-optical (RIZ) filter — will be combined with distances estimated from photometric redshifts ("photozs") to measure the dark energy equation of state. However, Euclid alone lacks the spectral energy distribution (SED) coverage needed to derive accurate photozs, so its long-wavelength (RIZ,Y,J,H) photometry will need to be combined with ugrizy data from LSST and other ground-based telescopes. The left panel of Figure 1 shows how adding UV-, u- and g-band imaging Euclid and LSST data improves the photoz measurements and allows a definitive characterization of dark energy. In particular, the short-wavelength data improves the photoz accuracy (particularly in the $0 < z < 1$ range) and reduces the number of catastrophic errors. The final redshift precision meets all requirements for an unbiased measurement of the dark energy equation of state based on gravitational lensing data

(Albrecht et al. 2006; Huterer et al. 2006), and should ultimately result in sub-percent accuracy in the equation of state parameters w_0 and w_1.

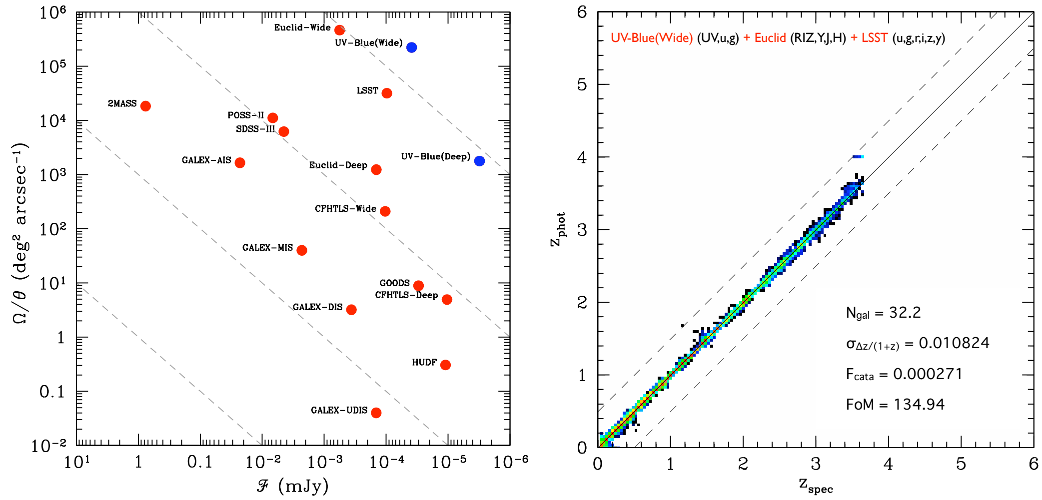

Figure 1. *(Left Panel) One representation of the "information content" of wide-field imaging surveys in the UV, optical and IR spectral regions. The abscissa gives the depth of each survey in mJy while the ordinate shows between Ω, the survey area in deg², and θ, the FWHM in arcseconds. Information content increases diagonally toward the upper right corner: i.e., dashed lines are separated by factors of a thousand in Ω/θF . (Right Panel) Comparison between photometric, z_{phot}, and spectroscopic redshifts, z_{spec}, based on simulated galaxy catalogs computed as described in Sorba & Sawicki (2011). The comparison assumes that RIZ,Y,J,H data from Euclid are combined with the end-of-survey data from LSST (u,g,r,i,z,y) and UV,u,g data from a ~1m space telescope that surveys an area of 5000 deg² to a depth of u=27.1 mag.*

The Structure of Dark Matter Halos from Lensing Magnification: Structure growth can be probed by looking at the abundance of massive, gravitationally-bound objects as function of redshift — a well known technique that can be used to set constraints on dark energy. The accurate photozs obtained by combining the UV/blue-optical imaging with data from Euclid and LSST (Figure 1) can be used to identify clusters from a few 10^{13} to 10^{15} $M_\odot$ using matched filter, red sequence, or max BCG methods. The 0.15 to 2 μm region is ideal for the matched filter approach which offers the advantage of being only weakly dependent on precisely how clusters are defined. Tight constraints on dark energy will then come from the large number of high-z clusters identified with this technique, which can be combined with magnification measurements to place independent limits on the dark energy equation of state over the range $0 \leq z \leq 2$.

Cosmic Shear and Galaxy Shapes: Although Euclid will provide excellent space-based imaging for galaxy shape measurements, there remains some concern that complications could arise from the use of a single, broad, visible filter for the shape measurements. Technically, this complication comes from the fact that stars (which are used to correct the effects of the PSF) do not have the same SEDs as galaxies. In other words, one cannot directly use stellar PSFs to correct galaxy shapes, as it is necessary to account for possible "gradient color" effects. While this problem can in principle be addressed via extensive SED simulations, the use of narrower u and g filters provide a unique way to explore the gradient color effect directly — on real data — without relying on simulated SEDs. Moreover, galaxy shapes measured directly from the u and g images could be used to characterize possible systematic errors in the shape measurements carried out at longer wavelengths with Euclid.

2. Galaxy Evolution

Evolution of Cosmic Star Formation and Stellar Mass: A survey of 5000 deg² in the LSST and Euclid survey regions would provide data spanning the UV to IR region for billions of galaxies. Photozs for galaxies in this sample (Figure 1) could be measured to a precision of $\Delta z < 0.02(1 + z)$, and the observed SEDs fitted with theoretical models to constrain their physical parameters. The long-wavelength data are critical for establishing the stellar mass and constraining the dust reddening and metallicity, while the instantaneous star formation rate (on timescales of $\tau \sim 10^8$ yr) can be measured from the flux from the massive stars that dominate the SED at $\lambda \leq 0.4\mu$m. UV imaging would be ideal for measuring this flux for galaxies out to z~1, while u-band data will serve the same purpose at $1 < z \leq 1.5$. Because the (UV-u) color index is a good indicator of dust extinction, it would allow, together with the LSST/Euclid data, robust measurements of the intrinsic star formation rate (SFR) and the stellar mass function and clustering of galaxies with different SFRs. The clustering analysis would also provide a measurement of the halo masses, and this technique could be used to trace how the connection between halo and stellar mass evolves and to link the growth of stellar mass to the mass assembly history of dark halos.

Dark Matter and Strong Lensing: Strong lenses are important cosmological probes of both galaxy dynamics and the structure of dark matter halos. Despite their importance, relatively few systems have been identified to date; mostt come from the SDSS spectroscopic database or wide-field imaging surveys with ground-based telescopes. In nearly all cases, high-resolution imaging from HST is needed to confirm their nature and to give reliable constraints on the gravitational potential of the lensing galaxy. An imaging survey of 5000 deg^2 at HST-like resolution has the potential to uncover >1000 strong lenses — roughly an order of magnitude increase over current samples. Thanks to the depth and resolution of the UV/blue optical imaging, it will be possible to establish quickly the morphology of the lenses, constrain the properties of the source galaxies, and explore the structure of galaxy-scale dark matter halos and their evolution with redshift.

QSOs and Active Galactic Nuclei: UV imaging allows QSOs to be selected efficiently in a variety of redshift ranges. For example, UV-, u- and g-band imaging allows high-purity QSO samples to be assembled in the ranges $1 \leq z \leq 2$ and $2 \leq z \leq 4$, with flux alone limiting the selection. Moreover, the high resolution of the imaging will make it possible to carry out morphological studies of these QSOs and their nearby companions. At the depth of the Wide Survey, it will be possible to identify QSOs with absolute g-band magnitudes $M_g \approx -22$ at $z = 4$, and several magnitudes fainter than this at the lowest redshifts, thus reaching deep into the regime of low-luminosity "Seyfert-type" galaxies. This would be the largest and most complete sample of QSOs and AGN at these redshifts, providing uniquely powerful constraints on QSO evolution. Monitoring observations would provide important information on the innermost regions of QSO accretion disks, which are probed directly by their UV- and u-band emission.

3. Near-Field Cosmology

The Halo Structure, Stellar Populations, and Accretion Histories of Nearby Galaxies: The history of mergers and accretions in luminous galaxies — which are powerful constraints on models of hierarchical galaxy formation — can be examined directly using the resolved stellar populations that make up their extended halos. Numerical simulations carried out in the framework of ΛCDM models make clear predictions for the number and morphology of satellites, shells, and streams within the halos of $z \sim 0$ galaxies. With a relatively shallow survey that focuses exclusively on long-wavelength observations, Euclid will be limited in its ability to probe the stellar populations in nearby galaxies. At the same time, severe crowding makes studying their resolved stellar populations with ground-based telescopes (e.g., LSST, Pan-STARRs) virtually impossible for all but the nearest systems (nor can ground-based facilities probe the UV region, where the emission from young/hot stars is largest). A wide-field, UV/blue-optical imaging facility with HST-like resolution would revolutionize our understanding of the nearest galaxies.

Compact Stellar Systems: One of the most exciting questions to have emerged from the study of nearby galaxy clusters during the past decade is the origin of the faintest and most compact stellar systems. The relationship between these so-called "ultra-compact dwarf" galaxies (UCDs) and massive star clusters remains obscure, largely because there exists no comprehensive (i.e., complete and unbiased) catalog of star clusters and UCDs within even a single environment. By combining wide field with its excellent sensitivity and superb image quality, it would be possible to carry out the first complete, and unbiased, survey of compact, low-luminosity objects in the local volume. For instance, a two-week survey of the Virgo cluster would allow a complete census of all compact stellar systems down to g ≈ 28 (equivalent to a limiting stellar mass of roughly $5000M_\odot$) and resolve individual UCDs, star clusters and dwarf galaxies with sizes as small as $R_e \approx 3$ pc. Such observations would provide a wealth of information (such as luminosities, stellar masses, concentration indices, mean surface densities and spatial distributions) that can be used to test models for their formation and evolution.

The Central Structure of Nearby Galaxies: Another surprising discovery from HST surveys undertaken during the past 10–15 years has been detection of compact, structurally-distinct stellar components at the centers of most intermediate- and low-mass galaxies. Since these compact stellar nuclei are found in galaxies spanning the entire Hubble sequence, it is clear that a rather generic formation mechanism is needed to explain this ubiquity. A UV/blue-optical imager with a wide field of view and a resolution comparable to HST would allow the definitive study of the core vs. global structure for many thousands of galaxies in field, group and cluster environments. Given the low luminosities of these nuclei (typically less than ~1% of the host galaxy luminosity) and their small sizes ($R_e \lesssim 0.1''$ at the distance of the Virgo cluster), such a facility offers the only hope of identifying and studying these nuclei in a systematic and unbiased way.

4. Stellar Astrophysics

High-resolution imaging from the Wide Survey (as well as from deep, pointed observations of nearby galaxies) would allow comprehensive studies of the young stellar populations in the local universe, including ***hot massive stars***. For instance, in exposures of just 30 minutes, it would be possible to detect $9M_\odot$ main-sequence (B0) stars in the Virgo Cluster, and $2M_\odot$ (A0) stars in M31. Crowding in these fields will pose a severe problem for all other facilities, including ground-based telescopes like LSST. ***Pulsating variable stars*** (including Cepheids and RR Lyraes) could be detected and studied in nearby galaxies with unprecedented samples and precision. For example, RR Lyraes in Local Group galaxies could be detected with nearly 100% completeness in just ~30 minute exposures. ***Symbiotic binaries***, in which the components have similar luminosity but very different temperatures, have traditionally been discovered serendipitously but they could be detected large numbers in the legacy surveys and GO programs. This would allow a global study of this important stage of evolution in nearby galaxies and, for the first time, a detailed comparison between observations and the predictions of stellar evolution models. ***X-ray binaries and transients,*** which have not been studied fully in Local Group galaxies despite their significance in understanding both star formation and the fundamental physics of extreme objects, could also be readily identified. Other types of "stellar exotica" could also be detected and studied, such as ***post-AGB stars*** (which are of interest both for stellar evolution theory and for understanding the nature of the emission from LINER galaxies) and ***planetary nebulae***, which can be detected via their characteristic emission-line properties. Finally, a facility of this sort would be an ideal instrument for dedicated, wide-area searches for hot and/or ***extremely metal-poor stars*** in the Galactic halo (relying on selection in the color-color diagram). In the Wide Survey, each pointing would contain ~7000 halo stars brighter than g = 27.8, so there is an almost limitless potential for studying the stellar populations in the Galactic halo.

5. The Outer Solar System

Mapping the Outer Solar System. The outer solar system (OSS) represents the most accessible laboratory for understanding the details of planet formation and evolution. Yet we are remarkably ignorant of its structure and composition, with only two objects known to have pericenter distances > 47 AU. Surveys with even the best ground-based telescopes are fundamentally limited in two distinct ways: (1) Deep surveys, like the CFHTLS, do not cover sufficient area to be sensitive to rare and distant (> 60 AU) solar system objects; while (2) surveys that cover sufficient area do not have the image quality or cadence needed to detect very distant objects. However, nearly diffraction-limited g-band images from a 1m-class telescope can reach very deep levels in short exposure times, allowing faint OSS objects to be detected in successive exposures. For instance, in the 5000 deg^2 Wide Survey region, observations to an equivalent depth of r ~ 26 with a cadence of three exposures per hour should detect ~50 OSS objects at distances > 400 AU. The total number of OSS objects that would be detected in such a survey is estimated to be ~20000, compared to the ~1500 OSS objects known at the present time.

Stellar Occultations and the Size-Frequency Distribution. The size-frequency distribution (SFD) of Kuiper Belt objects is an excellent probe of the processes of planetesimal formation. The ~20000 OSS objects that would likely be detected in a Wide Survey would allow an excellent measurement of the SFD for OSS objects, although the SFD transition that is expected to have arisen from *collisional processing* probably occurs in objects that are so small and faint (r ~ 33) that it is beyond the reach of any facility that relies on reflected sunlight. An alternative is to rely on serendipitous occultations of stars by passing Kuiper Belt and Inner Oort Cloud objects. This is the only technique that is sensitive to sub-km objects in the OSS, and it clearly requires a space-based observing platform. With a detector focal plane that is capable of reading 300 sampling regions (ROIs) at 10-20 Hz sample speed, it should be possible to detect multiple occultations by small (sub-km) OSS objects, and hence provide a first characterization of the SFD.

Surface Chemistry of OSS Objects. Spectroscopic studies for small bodies in the asteroid belt, including broadband measurements of SEDs, have played a key role in piecing together the formation history of the solar system. While one would like to extend these successes to OSS objects, they clearly exhibit ice as a dominant component — something which is obviously not true for asteroids. Characterization of these ices remains elusive, and even their identification is possible only for water-ice and methane which happen to exhibit deep absorption features at near-IR wavelengths. Broadband colors for OSS objects reveal a curvature of their reflectance slope (or color) in the u-band to more neutral colors than is seen in the optical. This has been interpreted as evidence for organic ice, which exhibits a similar behavior. The shape of this flattening into the UV region is not only a diagnostic of the what surfaces ices may exist, but also of the amount of radiation-induced chemistry the ices have undergone. The coarseness of available data (primarily broadband colors) prevents quantitative interpretation of the observations. Depending on the adopted observing strategy and cadence, the Wide Survey could detect up to ~20000 OSS objects, including ~800 with high-quality u- and g-band data (compared to only ~10 for which u-band fluxes are currently available). Such data would allow the first robust characterization of the SEDs of OSS objects, and would make it possible to not only constrain the types of ice that exist in the OSS, but also to explore both the nature of the primordial ices from which that these bodies originated and the chemical pathways that gave rise to them.

VI. Education and Public Outreach

Panoramic, high-resolution UV/optical imaging would not only transform astronomical research, but it would likely capture the public imagination in a way that few, if any, previous missions have managed. While HST remains the "gold standard" in terms of public visibility for astronomical facilities, a UV/optical imaging mission with a ~ two order-of-magnitude increase in field of view relative to HST, combined with an operations model that places high priority on wide-field legacy surveys, has the potential to rival, or even exceed, HST in its ability to convey the beauty and importance of science, technology and research to the public. It would also be an extraordinary teaching tool, offering many opportunities for students of all ages to experience the joys of scientific discovery first-hand through outreach programs like *Galaxy Zoo*.

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Unique Astrophysics in the Lyman Ultraviolet

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Summary: There is unique and groundbreaking science to be done with a new generation of UV spectrographs that cover wavelengths in the "Lyman Ultraviolet" (LUV; 912 - 1216 Å). There is no ***astrophysical*** *basis for truncating spectroscopic wavelength coverage anywhere between the atmospheric cutoff (3100 Å) and the Lyman limit (912 Å); the usual reasons this happens are all technical. The unique science available in the LUV includes critical problems in astrophysics ranging from the habitability of exoplanets to the reionization of the IGM. Crucially, the local Universe ($z \lesssim 0.1$) is entirely closed to many key physical diagnostics without access to the LUV. These compelling scientific problems require overcoming these technical barriers so that future UV spectrographs can extend coverage to the Lyman limit at 912 Å.*

The bifurcated history of the Space UV: Much the course of space astrophysics can be traced to the optical properties of ozone (O_3) and magnesium fluoride (MgF_2). The first causes the space UV, and the second divides the "HST UV" (1150 - 3100 Å) and the "FUSE UV" (900 - 1200 Å). This short paper argues that some critical problems in astrophysics are best solved by a future generation of high-resolution UV spectrographs that observe all wavelengths between the Lyman limit and the atmospheric cutoff.

Of the major facilities of space UV astronomy (Table 1), only Copernicus and FUSE have covered the LUV, and only FUSE carried modern photon-counting detectors. IUE and HST's spectrographs (until recently) covered only $\lambda > 1150$ Å because the common MgF_2 optical coatings have a ~50x drop in reflectivity between 1150 and 1100 Å. COS now has limited LUV capability ($A_{eff} \sim 10$ cm^2) because its design places these wavelengths onto its detector and the HST mirror coating is relatively clean after 20+ years (McCandliss et al. 2010, Osterman et al. 2010). However, this FUSE-like performance works well only for UV-bright objects and will not solve the critical problems that we describe here.

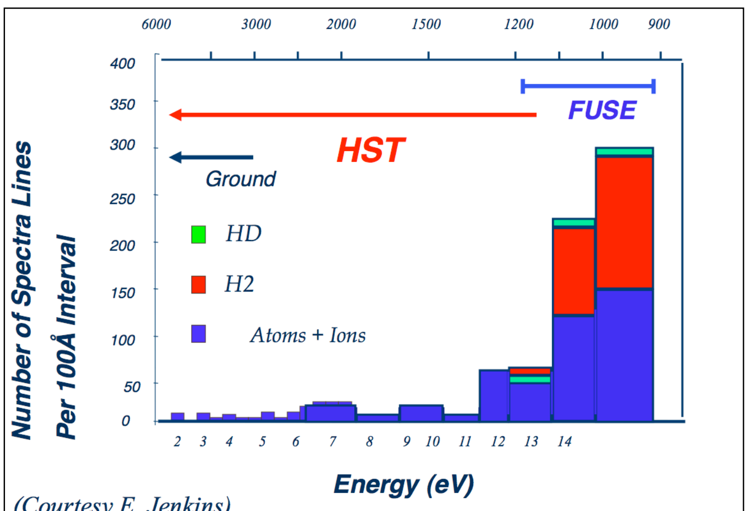

Figure 1: The density of absorption-line diagnostics as a function of wavelength. The ranges for HST, FUSE and ground apply to lines observed at the **rest-frame** wavelengths at the top. Many key science cases rely on redshifting < 900 Å EUV lines into the LUV (Tripp et al. RFI response).

The Key Reason to Cover the LUV is the extremely rich set of unique physical diagnostics that are available there. Figure 1 shows the continuously increasing density of all spectroscopic line diagnostics toward the LUV. The most commonly used LUV tracers include: (1) the doublet

[1] STScI [2]Colorado [3]JHU [4]UMass [5]Princeton [6]Notre Dame [7]GSFC [8]Wisconsin [9]Santa Cruz

Table 1: UV Spectrographs and Their Wavelength Coverage

Mission		Lifetime	UV Coverage (Å)
Copernicus		1972 - 1981	900 - 3150
IUE		1978 - 1996	1150 - 3200
FUSE		1999 - 2007	900 - 1190
HST	FOS	1990 - 1997	1150 - 8000
	GHRS	1990 - 1997	1150 - 3200
	STIS	1997- now	1150 - 3200
	COS	2009 - now	Cyc 17-19: 1140 - 3200 Cyc 20+: 900 - 3200

of O VI (O^{+5}), which traces coronal gas in the ISM and IGM, (2) the Lyman-Werner bands of molecular hydrogen, which can be detected in column densities orders of magnitude lower than those accessible to radio measurements, (3) species like Ne VIII, S VI, Fe XVIII, and Mg X, which trace gas at $\gtrsim 10^{5-6}$ K in stellar flares, AGN outflows, and IGM gas, (4) the Lyman series itself (912 - 1216 Å), the most sensitive probe of neutral gas anywhere on the EM spectrum. These diagnostic lines provide access to gas from below 100 K to above 10 million K, and from the underdense IGM (10^{12} cm^{-2}) to the edges of giant molecular clouds (10^{21} cm^{-2}). *They are versatile, essential tools of astrophysics which we must observe in the LUV if we are to see them in the local Universe* (e.g. in the rest frame). We need to access these important tracers everywhere, thus our major conclusion:

There is no *astrophysical* reason to break spectroscopic wavelength coverage anywhere between the atmospheric cutoff and the Lyman limit.

History teaches that such breaks are driven by the availability of optical coatings and detectors, and that astrophysical goals are often compromised to conform to technical limitations of these components. We will now consider some illustrative scientific opportunities remaining untapped in the LUV, covering a wide wide range of astrophysics from exoplanets to the reionization of the IGM. A full range of additional UV science was covered in the recent "UV Astronomy: HST and Beyond" conference which featured many excellent talks now posted online (http://uvastro2012.colorado.edu/).

UV Radiation and the Formation of Biosignatures

Stars set the conditions for life on their planets. Stellar characterization is critical to our understanding of exoplanetary life, particularly in light of the growing number of Earth-mass planets detected around low-mass stars (Batalha et al. 2012). A major source of uncertainty in the potential habitability of these worlds is the strength and variability of the local radiation fields where liquid water can persist (the "habitable zone", or HZ). Stellar flares can irradiate the exoplanetary atmosphere with heavy doses of X-ray and UV photons, potentially catalyzing or retarding the development of biology on these worlds through effects on molecular chemistry. The amplitude and frequency of UV flares on low-mass exoplanet hosts is completely unknown at present; time-resolved LUV observations are an essential input for models of habitable planets.

The large (LUV+FUV)/NUV stellar flux ratios in the HZ around M-dwarfs can have a profound effect on the atmospheric oxygen chemistry of Earth-like planets (France et al. 2012). Lyα itself is a critical energy input to the atmospheres, particularly the photochemistry of water and CO_2, because it contributes as much as all the rest of the 900-3000 Å range combined for stars with $T_{eff} \leq 4000$ K. The abiotic O_2 production rate (through CO_2 dissociation) and the subsequent formation of O_3 are highly dependent on the spectral and temporal behavior of the LUV, FUV, and NUV radiation field of the host stars. LUV lines from species such as O VI and FeXVIII are excellent proxies for the EUV and soft X-ray emission from low-mass stars (Redfield et al. 2003), which can estimate the energy deposition onto the planetary atmosphere without costly or impractical EUV and X-ray observations. But only three of the over 100 M-dwarfs known to host planets have well-characterized UV spectra, which hampers our ability to accurately predict the biosignatures from these worlds (Kaltenegger et al. 2011). Without direct measurements of stellar UV emission, we will not be able to assess the potential of false positives for biomarkers that may be detected in the coming decade.

With a future high-sensitivity UV mission employing photon-counting detectors and covering the LUV through the atmospheric cutoff, we will be able to survey all of the known M-dwarf exoplanet host stars at <50 pc (and K-dwarfs to > 200 pc), including all of the systems that can be studied in detail by JWST. These UV tracers provide a complete picture of the energetic radiation environment in which potentially habitable planets are immersed; directly related to the conditions for and detectability of life on these worlds.

The Circumgalactic Medium in High Fidelity

How galaxies acquire their gas, process it, and return it to their environment as feedback are some of the most important issues in astrophysics. But the Circumgalactic Medium (CGM) - where the accretion and feedback actually occur - is still *terra incognita* because it has such low density and because UV-bright QSOs behind nearby galaxies are rare.

COS has recently opened more territory to explorations of the CGM by increasing the number of accessible QSOs about 20-fold. The COS-Halos survey (Tumlinson et al. 2011) has exploited this capability to systematically survey the halos of 50 L* galaxies at $z \sim 0.2$ with one QSO each. We have used the O VI λλ1032,1038 doublet to show that the CGM of star-forming galaxies contains as much oxygen as their dense ISM, with major consequences for galactic feedback and chemical evolution. We have also found that the halos of “red and dead” galaxies have a surprisingly large amount of cold, bound gas in their halos, indicating that quenching of star formation does not totally remove the halo gas reservoir. O VI and EUV lines such as Ne VIII and Mg X (redshifted into the LUV) are better for these studies than tracers at longer wavelengths (such as CIV) because they probe higher temperatures and are less likely to come from cool photoionized gas.

The LUV wavelength range was closed to COS-Halos, so it targeted galaxies at $z \gtrsim 0.12$ to place O VI λλ1032,1038 at > 1140 Å, the shortest wavelength available with good sensitivity given the HST primary mirror coating. The price of this constraint appears in Figure 2, which shows the parent sample of QSO/galaxy pairs from which the COS-Halos sample was drawn. The redshift $z > 0.11$ required to place the O VI doublet into the COS band means that galaxies *closer* than 500 Mpc are not observable in O VI, and the entire SDSS spectroscopic survey is *off limits* to this critical diagnostic! Owing to sensitivity and wavelength coverage, HST and FUSE can access only a tiny fraction of the CGM gas that could be observed if we had access to fainter QSOs and the LUV. This science also requires high spectral resolution (R > 50,000) to resolve the cold gas associated with low-metallicity CGM clouds and other ISM lines in different environments.

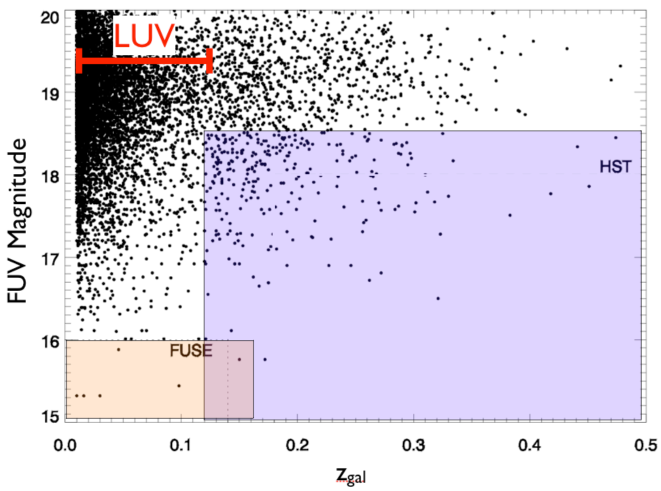

Figure 2: FUV accessibility to O VI, the key tracer of highly ionized CGM gas. Because of their limited sensitivity and wavelength coverage, HST and FUSE are still only able to probe a small fraction of the existing QSO galaxy pairs (black dots) that could be used to probe the CGM.

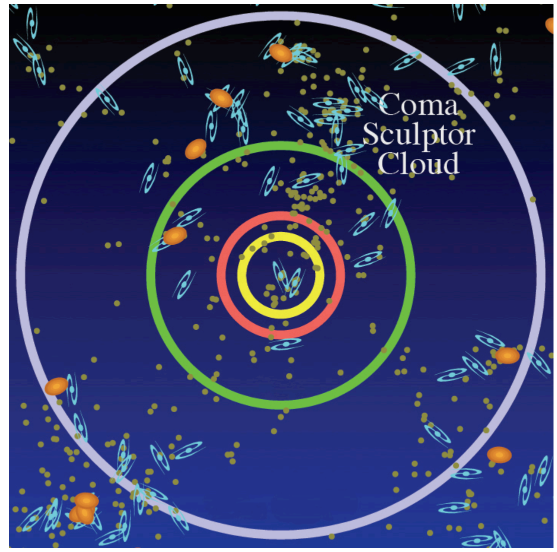

Figure 3: The outer circle is region of the local Universe where we can achieve > 10 QSOs behind every galaxy for highly resolved probes of the CGM with a telescope 100x HST sensitivity. However, without the LUV, a region **100000x** the volume of this sphere is **closed** to the key physical diagnostics of CGM gas.

Figure 3 illustrates another discovery space that could be opened with a future mission. A UV spectrograph with 100x the sensitivity of COS, which would be viable on an 8-m telescope, could observe *>10 QSOs behind every galaxy* out to 10 Mpc (the light purple) to weigh their CGM and relate its inflow and outflow to the stars and structure of fully resolved galaxies. Where COS-Halos is limited to studying mainstream L* galaxies, a future survey could effectively make a movie of the mass, metallicity, kinematics of the CGM in every phase of galaxy evolution from starbursts, to AGN, to passive evolution. A next-generation spectrograph could trigger another revolution in our understanding of the gas around galaxies and its role in galaxy formation. But without the LUV, this discovery space will be closed and a volume 100,000 times larger than the region of Figure 3 would still be inaccessible to the most important gas tracers.

Chemical Feedback in Galaxies

Star-forming galaxies (SFGs) are characterized by a large reservoir of HI (≤ 90-95% of the baryonic matter, Kniazev et al. 2000), which can hide the bulk of the interstellar metals. Measuring the metal content in this gas phase is critical for a proper accounting of all the baryons and the LUV wavelength range is key to this census. Massive stars of type O and B can be used very effectively in the Local Volume to probe abundances in the ISM and gas flows in and out of the disk. With ~ 10-20 OB stars per kpc^2 in a star-forming galaxy like the LMC or larger, the distribution of the metals on local scales of the order of 100 pc can be mapped and correlated with the local SFR.

Access to the LUV is critical for these studies. First, it allows access to the the full Lyman series for accurate measurements of total gas content, and it covers the optimal oxygen transitions for measuring gas-phase abundances. However, oxygen measurements in the neutral ISM are severely compromised by saturation in the strong O I λ1302 line and the near total absence of other O lines strong enough to detect in the FUV. Access to the LUV gives access to many O transitions of varying strength that would allow a more accurate estimate of the O abundances in the neutral gas for direct comparison with HII regions.

Furthermore, the LUV added to 1200-3200 Å gives access to all the gas phases, including the cold molecular gas traced by H_2 (100 K), hot/coronal gas traced by OVI (10^{5-6} K), warm gas (10^4 K) due to shocks/photoionization, and cold neutral interstellar medium (<1000 K). If the LUV is accessed at 100x greater sensitivity than COS at ~ 1300 Å, an OB star with the typical flux that is detected at S/N ~ 10 in ~ 50 HST orbits at the edge of the Local Group (1 Mpc), could actually be detected in **all** SFGs within a 10 Mpc Local Volume (as in Figure 3). **With IFU or ~100-fold multi-object capability, we would achieve a 1000- or 10,000-fold gain over HST that would allow us to map all the gas phases of the ISM at 100 pc scales in all star-forming galaxies within a 10 Mpc Volume.** This would allow us to understand how metals are released and recycled into galaxies of different type (normal L* galaxies vs LMC-like irregulars or dwarfs) and to have a comprehensive picture of chemical feedback in the Local Universe.

Active Galactic Nuclei, Near and Far

Understanding how black holes accrete matter, grow through cosmic time, and influence their host galaxies is crucial for our understanding of galaxy evolution. The accretion disks powering most active galactic nuclei (AGN) emit most of their energy in the far and extreme ultraviolet energy range. Outflows from AGN, visible as blue-shifted ultraviolet and X-ray absorption lines from highly ionized species (Crenshaw et al. 2003), may be at the heart of feedback processes that regulate the growth of the host galaxy. For nearby ($z < 0.15$) AGN, the LUV band contains key spectral diagnostics (O VI and the Lyman lines) that let us measure the kinematics and abundance of outflowing gas from AGN. When combined with the doublets of C IV and N V, these enable the measurement of absolute abundances (Arav et al. 2007). The capability to cover the full 900—3200 Å band at COS sensitivities would enable such measurements for hundreds of AGN, permitting direct measurement of the absolute abundances of gas ejected by AGN into their host galaxies. These studies can be enabled using the same sample of hundreds of AGN chosen for studies of the CGM, described above.

At $0.2 < z < 2.0$, lines of Ne VIII, Na IX, Mg X, and Si XII fall in the 900—3200 Å band. These ions have ionization potentials comparable to the X-ray absorbing gas detected in bright, local AGN. They have currently only been seen in the brightest intermediate-redshift AGN (Telfer et al. 1998; Muzahid et al. 2012). An LUV spectrograph with R~20,000 and a throughput of 5x COS would enable the detailed kinematical study of these species in hundreds of AGN at $z > 0.2$ more sensitively than any proposed X-ray telescope.

The peak of the spectral energy distribution of most AGN is in the extreme ultraviolet (Shang et al. 2011). While thermal emission from an optically thick accretion disk forms the peak of the spectrum, the shape in the extreme ultraviolet and how this connects to the soft X-ray is largely unknown due to absorption by neutral hydrogen and helium in the Milky Way. At intermediate redshifts, this spectral region becomes directly visible; observations in the LUV band open more of the AGN SED to direct observation. AGN accretion disks that peak at ~1200 Å (Telfer et al. 2003) are too cool for thermal radiation to continue to the soft X-ray band (e.g., Done et al. 2012). Comptonization of the disk spectrum by a warm, ionized coronal layer can produce the soft X-ray excess. Direct observation of this portion of the spectrum in intermediate redshift AGN (z~1) and correlation with the longer-wavelength thermal continuum to study time lags associated with the Comptonized reprocessing would enable us to assess the geometry of the accretion disk in hundreds of AGN. Opening the LUV also allows observations of QSO rest-frame EUV continua, as well as strong EUV emission lines (Ne VIII, OII-V) that have been seen in QSO composite spectra with COS (Shull, Stevans, & Danforth 2012).

Lyman Continuum (LyC) at Low Redshift and the Reionization of the IGM

We know most of the universe is ionized, but how did it become so? The answer is shrouded by the extreme opacity of neutral H to the first ionizing sources that emerge in the epoch of reionization. Observations by WMAP and SDSS have bounded this epoch to between 0.4 - 1 Gyr after the Big Bang ($6 < z < 12$). A key goal of the JWST is to detect the sources responsible for reionization, which are thought to be large numbers of small star-forming galaxies. Their existence has been inferred from theoretical calculations, comparing the density of hydrogen to the density of ionizing photons emitted by the first stars. A fundamental parameter in these calculations is the fraction of ionizing photons that escape from star-forming galaxies. JWST cannot directly detect ionizing photons, due to the prevalence of Lyman Limit (LL) systems in the IGM with neutral hydrogen column densities in excess of 10^{17} cm^{-2}. Inoue & Iwata (2008) calculate that at $z = 5.8$ the probability is near zero for finding a line-of-sight with source transmission > 0.02 in the LyC and at $z = 3$ the probability is only 50% for line-of-sight transmission to be > 0.6.

McCandliss et al. (2008) argue that the sweet spot for directly detecting the escape of ionizing radiation from star-forming galaxies is at the lowest redshifts, below $z < 0.4$ where the Lyman edge lies between its rest value at 912 and 1276 Å. There the need to correct for attenuation by LL systems becomes vanishingly small. Moreover, the characteristic brightness of the star-forming population of galaxies is 4.5 magnitudes, nearly a factor of 100, higher at $z \sim 0.1$ than it is at $z = 3$. McCandliss et al. (2008) find, assuming an ionizing radiation escape fraction of 0.02, that the estimated characteristic brightness of the star-forming galaxy population in the Lyman continuum (LyC) is 10^{-17} erg cm^{-2} s^{-2} Å^{-1} (~ 25 AB magnitude), at $z = 0.1$, while it is 10^{-19} erg cm^{-2} s^{-2} Å^{-1} (~ 29.5 AB magnitude) at $z = 2$. Low-z observations of ionizing radiation escape from small star-forming galaxies, analogous to those responsible for reionization, can probe the escape faction parameter to the lowest levels, in a variety of spatially resolved regions, allowing insight into those environments that favor escape. Access to 912 Å instead of just 1150 Å opens up many more AGN targets at z = 2-2.8 that probe the later epoch of He II reionization driven by QSOs. Such observations will provide quantified constraint on the contributions of star-forming galaxies to the meta-galactic ionizing background across all epochs and confirm whether star-forming galaxies reionized the universe or not.

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White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)

by Mel Ulmer, Northwestern University

In a SPIE paper (Ulmer, 2009, Proc SPIE, 7222, 33) Ulmer outlined a 8-m telescope proposal with upgraded detectors and coating that would, in the UV range, be $\sim 100\times$ more sensitive than HST. However, funding circumstances have changed such that it would appear that a 2.4 m class telescope is about as "good as it gets." Thus, here we de-scope that mission to a 2.4m that would probably cost about $2G in today's dollars. The main point of the technology discussion that I present first is that vast improvements can be had in the optics and detectors such that a new mission, although not our "dream machine" would bring a factor of > 10 improvement. Second, I demonstrate that plenty of science can be done with a $> 10\times$ improvement.

1 Improvements With Technology Enhancements

For the details of the HST optics see Ford et al 1998 (Proc SPIE, 3356, 234 and references therein). From Ford et al we note that the transfer mirrors **IM2** and **IM3** produce net 34% efficiency at 350 nm. Then by removing the correcting **IM2** and **IM3** mirrors we can greatly improve optics efficiency over the HST system by about $3\times$. The optical telescope assembly (OTA) itself is only 62% @350 nm such that assuming an improvement to 70% is plausible. Then, let us improve by $\sim 2\times$ over the QE of WFC (about 40%) to give us a net gain of about 7 at 350nm. Thus, there is plenty of headroom for the UV even if a CCD is used.

In comparison, the microchannel plates (MCPs) on the HST only about about 5% net QE. The equivalent single photon detectors that will become available (*if NASA ever finds enough money to fund them from TRL3 to TRL6 or above*) that are GN based will be $\sim$ 70%. The gain over the HST would be at least 15 just with a detector advance! Then this system would allow us to do in 40 orbits what it takes HST 600. *Note in comparing with the MCP to the GaN APD, we are comparing zero read noise devices.* Having zero read noise vs CCDs with (say 3 electron read noise) *is important*, however, as shown in Fig 1 taken from web posted presentation given by Don Figer of RIT.

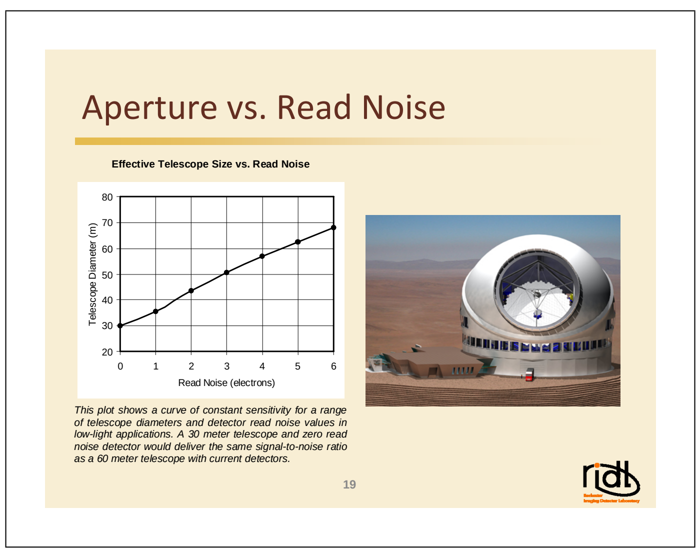

Figure 1: Read noise versus effective aperture

We see in Fig 1 that going from ~ 3 electrons (the WFC3 UV-Vis) camera to a zero-read-noise one gives us a boot of 50/30. Therefore, if we compare with an avalanche photodiode (APD) GaN zero-read-noise camera to a 40% QE CCD vs the 5% MCP we still get a gain of 50/30 by going to zero read noise. Including the 70%/40% gain in QE for the APD vs the CCD, the net is nearly 3. We are being conservative here in that the GaN does not require the severe blocking filters needed for cameras that are sensitive in the visible. Remember, we gain another factor of 3 by removing the transfer mirrors to then yield a gain of 9 over the current ACS/WFC in the near UV. Assume a 10% improvement in the OTA reflectivity to give an overall factor of 10 improvement; so in 100 orbits the next generation space UV-visible observatory (NG-SUVO) would be equivalent to the 1,000 orbits with HST!

Turning now to the Vis channels on HST: These only cover a field of view of about 3 arc min $\times$ 3 arc min. Yet, it should possible to gain a sky coverage factor of 4 with a 6 arc min $\times$ 6 arc min FOV. Then, combining zero read noise with the effective increase in étendue of the new mission would yield and improvement of about 6 total. This assumes no improvement in the reflectivity of the OTA, but a 10% improvement is possible. Also the current cameras have such slow readouts that for efficiency, the number of dithers and exposures is typically limited to 2-4. As CMOS advance, readouts can improve the observing duty cycle efficiency by ~ 1.5. Also it is plausible to gain of almost another factor of ~ 2 in efficiency with a zero read noise nearly 100% QE device. Therefore, even in the visible, gains can be made such that observations that benefit from a higher efficiency read outs, a 6 arc min $\times$ 6 arc min FOV (versus 3 $\times$ 3), zero-read-noise, and improved OTA reflectivity, the net gain will be 1.5 x 4 x 2 x 1.1 = 13!

All in all then significant advances can be made in the UV-Vis such that a 2.4 m telescope with modern detectors and coating will be a significant advance of HST even if it is not commensurate with our dreams of a 8 m or 16 m class UV-VIS mission.

Bottom line: Put significant funding into technology development to bring the key new detectors and coatings to at least TRL6, and we can then have a wonderful mission However, arguing for a new start without these improvements in hand will likely lead to either a new start being declined, or if accepted, not having the technology in hand such that a premature new start will likely lead to huge cost overruns.

2 Some Science Drivers

In order to keep this document short we simply enumerate some science drivers. As noted above see Ulmer, 2009, Proc SPIE, 7222, 33 for details:

2.1 Mainly UV

1. A study of the hot intracluster medium of rich clusters of galaxies: The concept is to use background QSOs along the line of sight to clusters to search for absorption lines due to gas as intermediate temperatures of about 10^5K to 10^6K. This gas *ought to be detectable* and detections will give us a link to the overall missing baryon question. However $\sim 50-100$ sight lines are needed to be assured of detections, and the necessity of about 50-100 targets then requires the increased sensitivity of the NG-SUVO.

2. He II absorption and the ionization history of the Universe out to z of 4.

3. Observing metals in intergalactic filaments

4. Observing the warm hot intergalactic medium (WHIM) and the relationship between galactic winds and metal enrichment of the WHIM.

5. Detecting metals in planetary disks leading toward an understanding the relationship between the metallicity in proto-planetary disks and planet formation.

6. Detecting the water absorption and perhaps even DNA-protein-like absorption features in the atmospheres of extra-solar planets (or extra-solar moons such as Europa or Enceladus).

7. Imaging aurorae on solar system planets, e.g. Jupiter

2.2 Mainly The Visible Band

1. Weak lensing mapping of Dark Matter.

2. Weak Lensing as a probe of the nature of Dark Energy.

3. Larger Deeper GOODs and UDFs (also UV as well).

4. With a coronagraph, imaging of planets (also in the UV as well).

5. Extending the catalog of Legacy images of nearby galaxies.