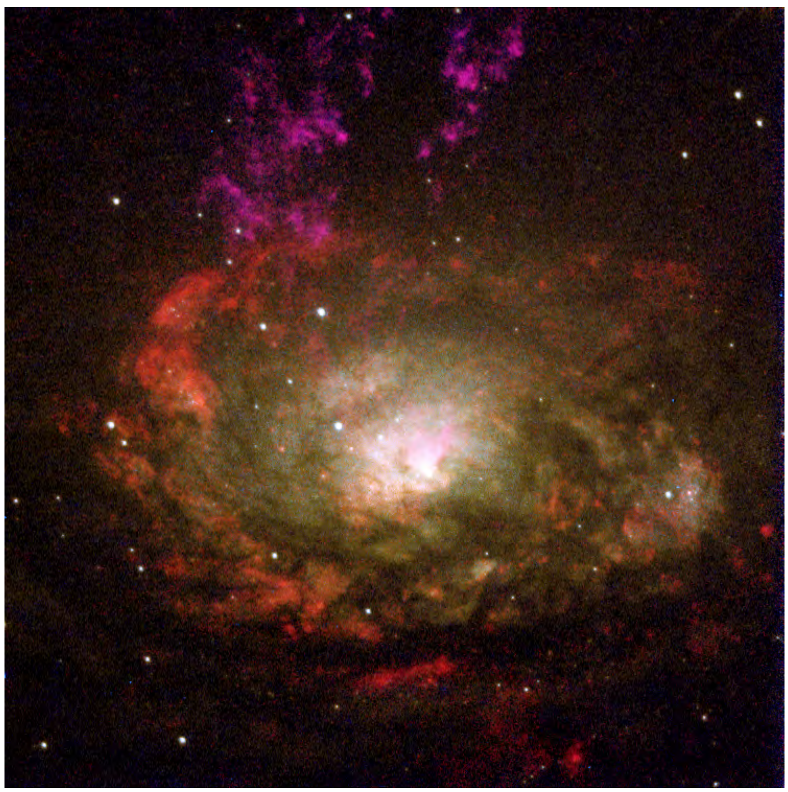
The Dusty Co-evolution of Black Holes and Galaxies: A Science Case for a Large Far-IR Space Telescope

A whitepaper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

L. Armus (lee@ipac.caltech.edu)
Infrared Processing and Analysis Center, Caltech

P.N. Appleton (IPAC), C.M. Bradford (JPL), T. Diaz-Santos (UDP), C.C. Hayward (Caltech), G. Helou (IPAC), P.F. Hopkins (Caltech), M.A. Malkan (UCLA), E.J. Murphy (IPAC), A. Pope (UMASS), B. Schulz (IPAC), H. Teplitz (IPAC)



Cover Image*: Hubble Space Telescope of the nearby Circinus galaxy. The dusty center shows evidence for a massive black hole, a powerful starburst, and outflows of hot gas.*

Background & Key Questions

In order to obtain a comprehensive picture of galaxy evolution, we need to accurately measure the growing population of stars and super-massive black holes in galactic dark matter halos. This evolution is determined by a complex interplay of physical processes (gravity, gas heating and cooling, star formation, black hole fueling, and feedback from star formation and AGN) that couple on scales ranging from < 1pc to tens of Mpc.

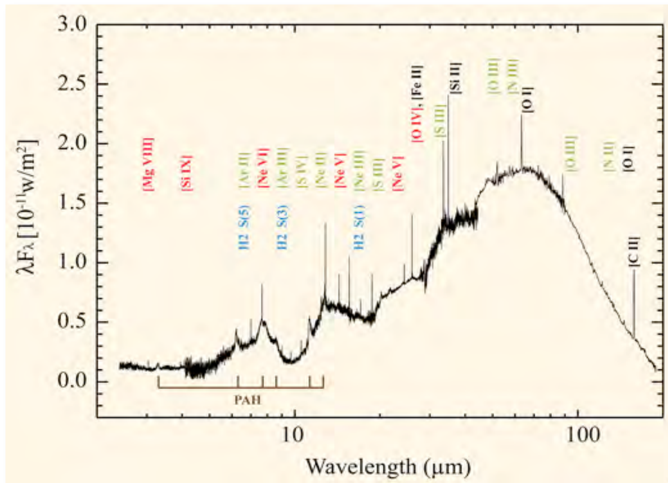
One of the most striking results to appear in the last decade has been the discovery that the mass of the central black hole and the stellar bulge in galaxies are correlated [11,17]. The idea that galaxies spend most of their lives on a star formation vs. stellar mass "main sequence" [48] further suggests that star formation and black hole accretion are intimately linked. Understanding how this relationship is built over time drives a great deal of observational and theoretical astrophysics, providing considerable motivation for the next generation of ground and space-based observatories. Despite the success of cosmological simulations that model the hierarchical growth of galaxies [7, 34, 35], and observations suggesting that periods of significant AGN accretion occur during episodes of enhanced nuclear star-formation [6, 9, 23], a number of critical questions still remain, such as: **When do the first heavy elements appear, and how does the chemical history of the Universe regulate the collapse of the first stars and the build-up of galaxies? How and when do the first black holes form and how does the black hole – bulge mass relation evolve with redshift for galaxies on and off the star forming main sequence? How and when does feedback from stellar winds, supernovae and AGN regulate star formation and the growth of galaxies?**

Although we have broadly measured the evolution of the bolometric luminosity density to z~3, the relative contribution of AGN and star formation at early epochs is quite uncertain. To piece together a complete picture of the co-evolution of galaxies and black holes requires the ability to make extremely sensitive infrared measurements of the most obscured regions at the centers of faint, distant galaxies.

The Need for Background-Limited FIR Spectroscopy

More than half of all the light emitted from stars is absorbed by dust and re-emitted in the infrared [8]. While traditional UV and optical diagnostics can be severely hampered by dust attenuation, FIR spectroscopy provides a direct measure of the basic physical properties (density, temperature, pressure, kinematics) of the ionized ($T\sim10^4$ K), the neutral atomic, and the warm (T~100-500 K) molecular gas in obscured galaxies. **It is the only part of the electromagnetic spectrum that gives a complete picture of all phases of the interstellar medium, from atoms to complex organic molecules.** The infrared is rich in fine-structure lines of Oxygen, Carbon, Nitrogen, Neon, Sulfur and Silicon covering a wide range in ionization potential, as well as molecular hydrogen and dust (Polycyclic Aromatic Hydrocarbons - PAHs). Together, these features constrain the strength and hardness of the interstellar radiation field [18, 3, 20]. This is extremely relevant since z~3, UV-selected galaxies seem to have starbursts with harder radiation fields, higher ionization potentials and/or different abundances than those at z~0 [50]. The FIR lines can be used to trace molecular outflows [37, 38] and infer the size of the starburst [39], and mid-J transitions of CO can distinguish starburst from AGN heating of the molecular gas [4, 30, 40, 41]. A FIR spectroscopic survey of high-redshift galaxies can solidly establish the history of early chemical enrichment, the rise of metals, and the presence of organic molecules.

With ISO, Spitzer and Herschel we have studied large samples of dusty galaxies in the local Universe [5, 2, 9, 42, 45, 46], identified PAHs in the most luminous galaxies out to z~4 [24, 19, 43] and detected the populations responsible for the bulk of the FIR background at z~1 [16]. However, our knowledge of how AGN and galaxies grow together, and the role of feedback in rapidly evolving, dusty galaxies at z >2-3 is extremely limited.



Infrared spectrum of the Circinus galaxy showing a strong dust continuum studded with features from small grains, ions, and warm molecular gas [21].

In order to produce a complete census of AGN and chart the growth of super-massive black holes and stellar mass in dusty galaxies across a significant fraction of the age of the Universe, a broadband, FIR spectrometer capable of reaching the natural astrophysical background over the ~30-300μm range is required. FIR cooling lines in z~2 IR galaxies should have fluxes ~10^{-19} Wm^{-2}. The rest-frame MIR lines will be 5-10x fainter. JWST will provide our first glimpse of the earliest galaxies, yet most of the mid-infrared diagnostic lines will pass out of the observable range of the JWST spectrographs by z~2. ALMA is already detecting z >5-6 galaxies [31, 44, 47, 49], yet it operates in limited atmospheric windows, and cannot access the rest-frame MIR spectral features. In particular, we require: **(1)** sensitivity of ~1×10^{-20} Wm^{-2} in an hour to detect normal dusty galaxies at z > 2 and luminous galaxies at z > 4, **(2)** broad spectral coverage from ~30-300 μm to cover the key redshifted MIR and FIR lines, **(3)** a spectral resolving power of R > 100 to separate individual atomic features from dust emission and absorption, and **(4)** spectral multiplexing to place 10-100 beams on the sky and allow for significant samples to be built up rapidly. The required sensitivity and wavelength coverage is impossible to reach from the ground, but could be achieved with a large, actively cooled telescope in space.

CALISTO, a cold T~4K, 5m class telescope which has been put forward for the FIR Surveyor concept (see Bradford et al. whitepaper), is the only mission currently envisioned for the next decade capable of achieving the goals outlined above. Through FIR spectra of thousands of distant galaxies, CALISTO will allow us to map out the history of galactic chemical enrichment, accurately estimate the bolometric fraction contributed by AGN and starbursts in even the most obscured sources, and trace AGN and stellar feedback via IR absorption and emission features providing a complete census of the buildup of galaxies and black holes over the past 10 Gyr.

References

[1] Alexander, D.M., et al. 2008, AJ, 135, 1968 ● [2] Armus, L. et al. 2007 ApJ, 656, 148 ● [3] Brauher, J.R., Dale, D.A., and Helou, G. 2008 ApJS, 178, 280 ● [4] Bradford, C.M. et al. 2003 ApJ, 586, 891 ● [5] Brandl, B.R. et al. 2006 ApJ, 653, 1129 ● [6] Daddi, E. et al. 2007, ApJ, 670, 156 ● [7] Vogelsberger, M., et al. 2014 Nature, 509, 177 ● [8] Elbaz, D., & Cesarsky, C. 2003 Science, 300, 270 ● [9] Farrah, D. et al. 2007, ApJ, 667, 149 ● [10] Ferrarese, L. & Merritt, D. 2000, ApJ, 539, 9L ● [11] Gebhardt, K., et al. 2000 ApJ, 539, 13L ● [12] Gonzalez-Alfonso, E., et al. 2004 ApJ, 613, 247 ● [13] Hopkins, P.F., et al. 2008, ApJS, 175, 390 ● [14] Huang, J.-S., et al. 2007, ApJ, 660, 69L ● [15] Lutz, D. et al. 2001, A&A, 378, 70L ● [16] Magnelli, B., et al. 2013, A&A, 553, 132 ● [17] Magorrian, J. et al. 1998, AJ, 115, 2285 ● [18] Malhotra, S., et al. 2001 ApJ, 561, 766 ● [19] Menendez-Delmestre, K. et al. 2007, ApJ, 655, 65L ● [20] Luhman, M.L., et al. 1998 ApJ, 499, 799L ● [21] Moorwood, A.F.M. 1999 ASPC, 177, 141 ● [22] Ogle, P., et al. 2007 ApJ, 668, 707 ● [23] Papovich, C., et al. 2007, ApJ, 668, 45 ● [24] Pope, A. et al. 2008, ApJ, 675, 1171 ● [25] Robertson, B., et al. 2006, ApJ, 645, 986 ● [26] Santoro, F. & Shull, J.M. 2006, ApJ, 643, 26 ● [27] Soifer, B.T., et al. 1984, ApJ, 283, L1 ● [28] Springel, V. & Hernquist, L. 2005, ApJ, 622, L9 ● [29] Walter, F., et al. 2009, Nature, 457, 699 ● [30] Weiß, A. et al. 2007, A&A, 467, 955 ● [31] Willott, C.J., et al. 2015, arXiv:1504.05875 ● [32] Yan, L. et al. 2005, ApJ, 628, 604 ● [33] Yu, Q. & Tremaine, S. 2002, MNRAS, 335, 96 ● [34] Hopkins, P.F., et al. 2014 MNRAS, 445, 581 ● [35] Schaye, J., et al. 2015, MNRAS, 446, 521 ● [36] Sturm, E., et al. 2010, A&A, 518, L36 ● [37] Sturm, E., et al. 2011, ApJ, 733, L16 ● [38] Veilleux, S., et al. 2013, ApJ, 776, 27 ● [39] Diaz-Santos, et al. 2013, ApJ, 774, 68 ● [40] van der Werf, P., et al. 2010, A&A, 518, L42 ● [41] Rosenberg, M.J.F., et al. 2015, ApJ, 801, 72 ● [42] Stierwalt, S., et al. 2013, ApJS, 206, 1 ● [43] Riechers, D.A., et al. 2014, ApJ, 786, 31 ● [44] Riechers, D.A., et al. 2014, ApJ, 796, 84 ● [45] Sturm, E., et al. 2000, A&A, 358, 451 ● [46] Genzel, R., et al. 1998, ApJ, 498, 579 ● [47] Capak, P. et al. 2015, Nature, in press ● [48] Elbaz, D., et al. 2011, A&A, 533, A119 ● [49] Maiolino, R., et al. 2015, MNRAS submitted ● [50] Steidel, C.C., et al. 2015, ApJ, 795, 165

Mapping Turbulent Energy Dissipation through Shocked Molecular Hydrogen in the Universe

A whitepaper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

P. N. Appleton (apple@ipac.caltech.edu)
NASA Herschel Science Center, Caltech
(626-395-3119)

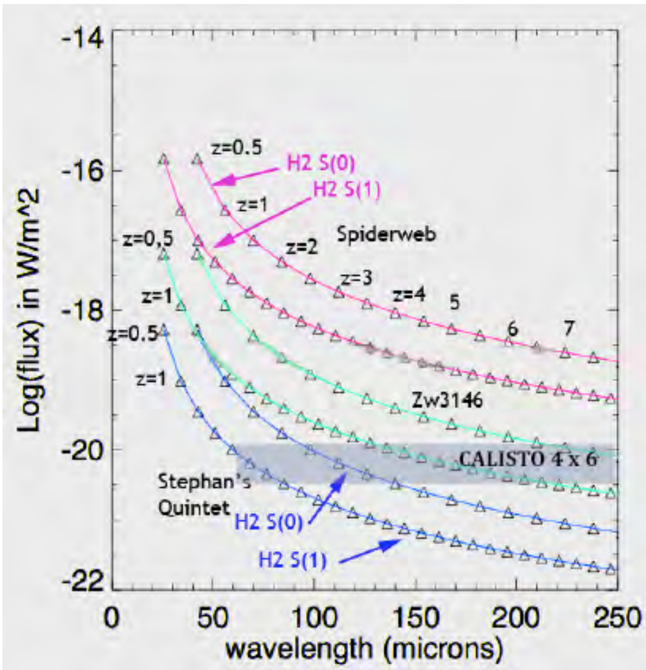
L. Armus (IPAC), C. M. Bradford (JPL), G. Helou (IPAC), P. Ogle (IPAC), A. Cooray (UC Irvine), J. Aguirre (U.Penn), Caitlin Casey (UC Irvine), Phil Mauskopf (ASU), Bade Uzgil (U. Penn/JPL), P. Guillard (IAP, Paris), F. Boulanger (IAS, Orsay)


Cover Images: ***(Left)*** *Shock-excited 0-0S(1) molecular hydrogen (blue) emission from Stephan's Quintet,* ***(Right)*** *The most extreme warm H_2 emitter found by Spitzer just before it ran out of cryogen--The "Spiderweb" proto-cluster at $z = 2.16$.*

Background and Motivation: Probing the growth of structure in the Universe is arguably one of the most important, yet uncharted areas of cosmology, ripe for exploration in the next few decades. Molecular hydrogen (H_2 and HD), along with the first heavy metals born in the first supernovae, played a vital role in cooling the primordial gas (e. g. Santoro & Shull 2006), setting the scene for the formation of first large-scale baryonic structures. The IGM enrichment by heavy elements also led to the formation of dust, which in turn almost certainly led to a rapid acceleration of H_2 formation on grains for redshifts z < 15 (Cazaux & Spaans 2004). Almost all the primary cooling channels for gas at z > 2 occur in the far-infrared/sub-mm bands, including dust and Polycyclic Aromatic Hydrocarbons (PAH) emission, the mid-IR rotational lines of molecular hydrogen (e. g. 0-0 S(3)9.7μm, S(1)17μm, S(0)28μm), and the far-IR lines of [O I]63μm, [Si II]34.8μm, [Fe II]25.9μm and [C II]157μm. **The far-IR is therefore a critical window for the study of the initial growth and evolution of gas in the universe over cosmic time.**

During the *Spitzer* mission, it was discovered that there exists a population of galaxies exhibiting extremely strong emission from warm (typically 100 < T < 500 K) molecular hydrogen (Ogle et al. 2010). One of the most striking examples was found in the giant intergalactic filament in Stephan's Quintet (Appleton et al. 2006, Cluver et al. 2010), where the mid-IR molecular hydrogen lines were unusually bright (Cover page). This warm molecular gas is believed to be tracing the dissipation of mechanical energy in shocks (Guillard et al. 2009) and turbulence, caused by the collision of a high-speed intruder galaxy with a tidal filament. H_2 emission dominates the gas cooling in the Quintet's filament, being enhanced relative to other important coolants (Appleton et al. 2013). Thus molecular hydrogen seems to be a powerful coolant, even in the local universe where metals are more abundant than in the early universe. Other nearby examples have also been found, where the H_2 appears to be heated by collisions between galaxies (Peterson et al. 2012, Cluver et al. 2013, Steirwalt et al. 2014). Furthermore, Ogle et al. (2010) showed that 20% of nearby 3CR radio galaxies also showed excessively high warm H_2 emission, most likely from shocks caused by the passage of the radio jets through the host galaxy (see also Nesvadba et al. 2010; Nesvadba et al. 2011). Guillard et al. (2012) demonstrated that radio galaxies exhibiting strong HI outflows also showed similar characteristics. In some cases, the warm molecular hydrogen provides clues about the suppression and removal of gas in the inner regions of galaxies containing AGN (Ogle et al. 2014). **Studying emission from warm molecular hydrogen can provide a direct measure of the properties of the gas cooling, which sets limits of timescale for the dissipation of turbulent energy. This is likely to be important for understanding the physical conditions that lead to negative ISM feedback on star formation in the universe.**

Bridging to the high-redshift Universe: Before *Spitzer* ran out of cryogen, it detected a number of very powerful H_2-emitting galaxies, including several central cluster galaxies (e. g. Zw 3146 at z = 0.3; Egami et al. (2006)), where the H_2 line-luminosity is an order of magnitude brighter than those seen in individual galaxy collisions. Shocks and or cosmic ray heating (Guillard et al. 2015; Ferland et al. 2008) may be responsible for some of these large luminosities, but by far the most powerful warm H_2 emitting system was detected by Ogle et al. (2012) in the z = 2.15 radio galaxy proto-cluster PKS1138-26 (knows as the "Spiderweb": cover page). The luminosity in a single H_2 rotational line (the 0-0 S(3) 9.66μm), was a phenomenal 3×10^{10} $L_{\odot}$, 100 x brighter than Stephan's Quintet. The existence of such extreme H_2 emitters begs the question of whether H_2 could be used to probe turbulence in the early universe (see Appleton et al. 2009). The molecular hydrogen lines therefore represent an important window into turbulence that can only be explored in the far-IR. Although JWST's mid-IR capability will allow the study of the nearby universe in the higher-excitation H_2 lines, **the exploration of H_2 in the low-lying rotational lines (which traces the dominant mass and cooler temperatures) will impossible beyond z > 2, without a large cool FIR telescope in space.**



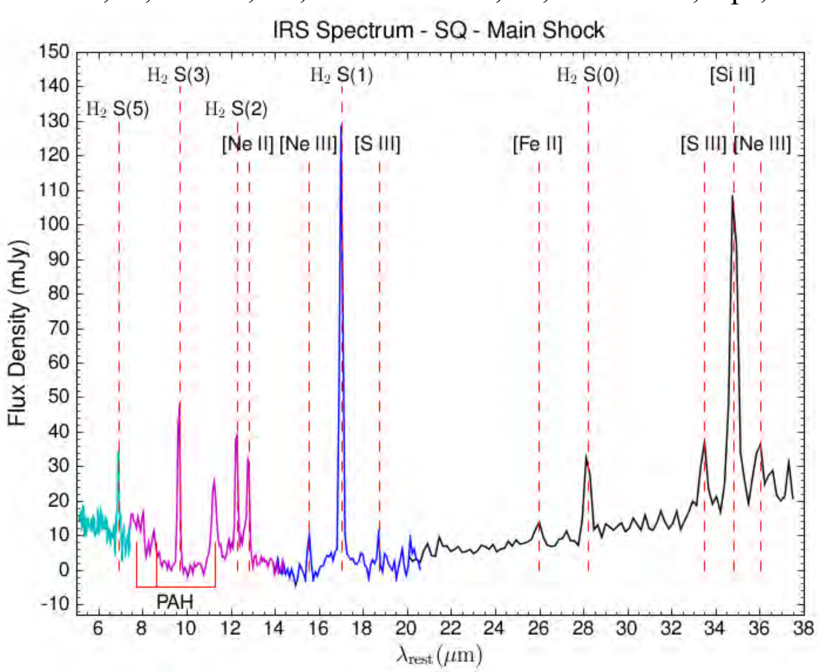
Estimates of the 0-0S(0)28μm and 0-0S(1)17μm ground-state pure-rotational H_2-line fluxes ($W\ m^{-2}$) for the Spiderweb (PKS1138-26) and the central cluster galaxy in Zw 3146 shifted in increments of z= 0.5 as a function of observed wavelength.

The grey box shows the achievable sensitivity of the CALISTO telescope with the 4 x 6 element spectrometer discussed by C. M. Bradford in an associated white paper. These sources, if they exist at higher-z, would be readily detected at z > 5-6. Compact group sources like Stephan's Quintet could be studied to z > 1.

Although the detection of individual proto-galaxies at redshifts > 10 are probably beyond the reach of current instrumentation (see Appleton et al. 2009), the detection of powerful clusters at z > 4 is quite feasible (see figure). These systems will provide an important insight into energy dissipation and galaxy formation in the most over-dense regions in the universe. CALISTO, a cold T~4K, 5m class telescope which has been put forward for the FIR surveyor concept (see Bradford et al. whitepaper), is the only mission currently envisioned for the next decade capable of detecting the low-excitation H_2 gas that we associate with large-scale turbulence. Extra sensitivity could be gained by mapping around strong lensing systems, to dig deeper, and to avoid foreground confusion. This would allow exploration of limited volumes of the high-z universe to greater depth. Potentially ALMA-Band 10 has a capability of reaching few x 10^{-20} W m^{-2} in long integrations. However, the tiny primary beam (5 arcsecs at 850 GHz), and narrow fractional band-width (< 0.3%) would make the detection of shocked-enhanced primordial gas extremely difficult, requiring *a priori* knowledge of the precise target location and redshift. CALISTO, on the other hand, can potential detect turbulent H_2 out to high redshift in many H_2 lines simultaneously because of its huge wavelength grasp. In addition, its larger beam would allow efficient mapping, especially if more than one beam is placed on the sky simultaneously (the 4 x 6 concept of Bradford et al.). At the highest z, the best way to detect primordial gas may be through the method of intensity mapping (e. g. Gong et al. 2013), where a CALISTO-like spectrometer could be used to map spatially and exploit spectrally, the faint statistical signals of proto-galaxies at z > 10. **A cold FIR telescope in space would provide a vital probe of heating and cooling processes at work in the youngest galaxies, greatly expanding NASA's portfolio, and providing a unique suite of tools for studying the Cosmic Dawn.**

References

Appleton, P. N., et al. 2006, ApJ, 639, L51.
Appleton, P. N., Guillard, P., Boulanger, F., et al. 2013, ApJ, 777, 66
Appleton, P., Armus, L., Blain, A., et al. 2009, in astro2010: The
Astronomy and Astrophysics Decadal Survey, vol. 2010 of ArXiv Astrophysics e-prints,
2. 0903.1839
Cazaux, S., & Spaans, M., 2004, ApJ, 611, 40
Cluver, M. E., Appleton, P. N., et al. 2010, ApJ, 710, 248.
Cluver, M. E., Appleton, P. N., Ogle, P., et al. 2013, ApJ, 765, 93
Egami et al 2006, ApJL, 652, L21
Ferland, G. J., Fabian, A. C., Hatch, N. A., et al. 2008, MNRAS, 386, L72
Gong,Y., Cooray, A & Santos, M. G., 2013, ApJ, 768, 130
Guillard, P., Boulanger, F., Pineau Des Forˆets, G., & Appleton, P. N. 2009, A&A, 502, 515
Guillard, P., Ogle, P.~M., Emonts, B.~H.~C., et al.\ 2012, \apj, 747, 95
Guillard, P., Boulanger, F., Lehnert, M.~D., et al. 2015, A&A, 574, 32
Nesvadba, N., et al. 2010, A&A, 521, A65. 1003.3449
Nesvadba, N. P. H., Boulanger, F., Lehnert, M. D., et al. 2011, A&A, 536, L5.
Ogle, P., Boulanger, F., Guillard, P., et al. 2010, ApJ, 724, 1193
Ogle, P.~M., Lanz, L., & Appleton, P. N.\2014, ApJL, 788, L33
Ogle, P., Davies, J. E., Appleton, P.~N., et al. 2012, ApJ, 751, 13
Peterson, B. W., Appleton, P. N. & Helou, G, et al. 2012, ApJ, 751, 11
Santoro & Shull (2006), MNRAS, 368, 26
Stierwalt, S., Armus, L., Charmandaris, V., et al. 2014, ApJ, 790, 124



The IRS spectrum of the turbulent shock structure in the Stephan's Quintet Compact Group (Appleton et al. 2006; Cluver et al. 2010). The warm H_2 gas dominates the power from the region. [CII]157μm (Appleton et al. 2013) and [SiII] emission are the next most powerful line coolants. These lines are redshifted into the far-IR and sub-mm at high-z.

Actuated Carbon Fiber Reinforced Polymer Mirror Development

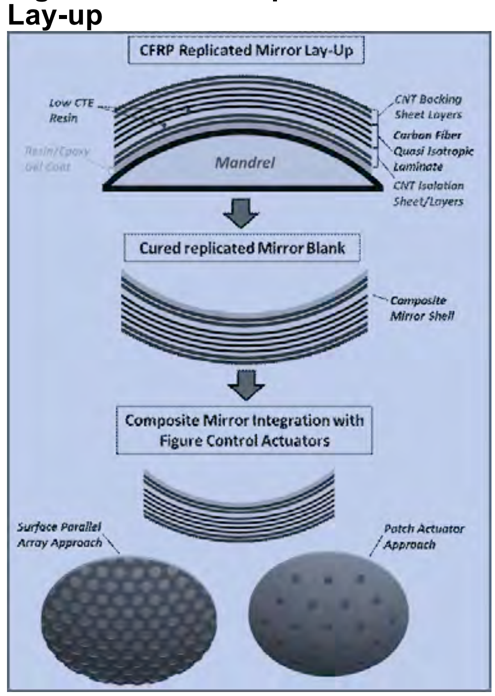
Brian Baldauf[1][a], Tony Magaldi[a], Russ Matijevich[b], Terry Bruno[b], John Vayda[b]
[a]Northrop Grumman Aerospace Systems, One Space Park Dr., Redondo Beach, CA 90278
[b]AOA Xinetics, 53 Jackson Road, Devens, MA 01434

The AURA Study of Future Space-Based Telescopes presented at the 225th meeting of the American Astronomical Society (AAS 225) details the compelling science case for launching a large-aperture, high resolution space telescope in the 2020s and points to the need to initiate technical development work now to inform the 2020 Astrophysics Decadal Survey. Whether we are seeking to observe the faintest objects in the universe or discern Earth-like planets hidden in the glare of their parent star, larger collecting areas in space are needed.

Astronomical flagship missions after James Webb Space Telescope (JWST) will require affordable larger aperture space telescopes and the science requirements may drive optical figure stability to as tight as 10's of picometers over 10's of minutes. Advances in lightweight mirror and metering structure materials such as Carbon Fiber Reinforced Polymer (CFRP) that have excellent mechanical and thermal properties, e.g. high stiffness, high modulus, high thermal conductivity, and ultra-low thermal expansion make these materials excellent candidates for a low cost, high performance Optical Telescope Assembly (OTA). It has been demonstrated that mirrors built from these materials can be rapidly replicated in a highly cost effective manner.

Telescopes of appropriate size, 10 to 20 meters, built via conventional substrate materials such as glass and Beryllium, will be prohibitively expensive and will take many years to fabricate. Active (actuated), replicated CFRP optics offer very low-cost scalable manufacturing, production times on the order of weeks vs years, minimal system level (expensive) ground testing, and low-mass. Removing the optics from the cost and schedule critical paths coupled with cost and schedule reductions will allow for production of larger apertures at lower areal densities thus making a 20 m segmented primary mirror possible from a cost/schedule perspective.

Figure 1. CFRP Replicated Mirror Lay-up



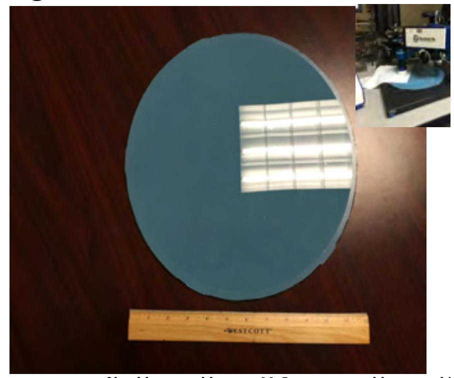
An Evolvable Space Telescope (EST) that is assembled in orbit can substantially reduce the cost of a large aperture optical system, establish science operations early, and spread funding requirements over several years. Actuated CFRP mirrors support the ability to expand/evolve the size over time via on-orbit assembly and alignment. We can leverage the early CFRP mirror development work at NGAS and establish the materials, designs, and processes necessary for large-format precision optics using state-of-the-art composite technologies.

Northrop Grumman Aerospace Systems with our subsidiary Adaptive Optics Associate Xinetics (AOX) have developed a novel approach to active carbon

[1]brian.baldauf@ngc.com; phone 1 310-813-0163; fax 1 310-813-3395; northropgrumman.com

composite optics (Figure 1). Our approach replicates a high-optical quality finish by laying-up the composite

Figure 2. 30 cm CFRP Flat Segment



directly on a super-polished mandrel and using special materials and processes to mitigate fiber print-through resulting in an optical quality surface finish. . We correct any residual wavefront errors due to spring-back, resin shrinkage or any other error sources with a low number of our actuators, a technique previously demonstrated at TRL 6 on SiC mirrors. These actuators not only correct manufacturing errors but combined with our demonstrated wavefront control approach also provide on-orbit fine alignment correction capability during in-space assembly or due to structural changes from outgassing. and the actuators use the same electroceramic material used to actuate the Articulating Fold Mirrors within Hubble's Wide Field Planetary Camera 2.
A recent independent R&D program yielded a promising surface roughness of 2nm and correctable low-order wavefront errors of 5-10 microns. We have successfully actuated 4 inch and 6 inch diameter samples, producing results which agree with our Finite Element Analysis (FEA) models. We are currently actuating a 12 inch sample (Figure 2). Our efforts in the near term will focus on improving surface finish to a few Angstroms, demonstrate the process on concave mirrors, then scale to the 1.5 to 2.5 m aperture sizes making them ideally suited to be integrated into an Evolvable Space Telescope (EST) architecture approaching the 10 to 20 m size. The emergence of commercially available Carbon Nanotube (CNT) and carbon nanofiber mat materials, and low CTE adhesives has allowed us to make substantial, rapid improvements in CFRP surface finish and figure.

Key advantages of CFRP optics over traditional optics substrates:

- Replicated optical surface (i.e. no polishing required)
- Low mass and low CTE
- Rapid production schedule compared to other substrates

Designing a large telescope to survive these first few minutes of its life during launch results in an over-designed structure compared to the on-orbit structural loads it will experience, thus driving up cost and expanding schedule.

Using our approach to CFRP optics, when combined with robotic assembly of an EST on orbit, minimizes launch-imposed design and cost constraints. Instead of a complex, fully assembled space telescope, we can launch bundled components on smaller rockets. We can optimally package our CFRP mirror segments within launch containers which would carry the launch loads. Once on orbit, the robotic assembly spacecraft would then connect each mirror segment to a mirror backplane and spacecraft launched previously. This approach will substantially reduce system costs, flatten funding requirements, and maximize the science product.

Astrophysics Enabled by Extreme Contrast Ratio Technologies

Daniel Batcheldor, Florida Institute of Technology
dbatcheldor@fit.edu

MOTIVATION

The most compelling questions in modern astrophysics now require the use of advanced data collection techniques that overcome the problems associated with extreme contrast ratios (ECRs). Internal/external coronagraphy, nulling interferometry, integral field spectral deconvolution and spectral differential imaging are all high-contrast ratio techniques each with their own advantages and disadvantages. For example, the need for high wave-front quality, precise pointing control, additional support structures, and multiple apertures, all lead to significant costs and complications. Software based PSF modeling like LOCI provides some incremental gains in faint point source detection when used with other methods, and the KLIP/ALICE approaches are limited to NICMOS/CORON observations. Consequently, new, cheap, and easy to implement techniques that can suppress the PSF and enable extreme contrast ratio imaging, would be of great benefit.

KEY SCIENCE QUESTION(S)

The direct imaging of an Earth-like planet around another star is probably the most obvious aim for our cosmic origins understanding. However, to image an exoearth one must be able to spatially separate the planet and star, so high resolution is required. In addition, the signal from the planet will be very low so high sensitivity is required. Finally, the magnitude differences between an exoplanet and host star are extreme so ECR imaging is needed. In the case of the Sun-Earth system the difference is 23 magnitudes requiring a $10^{9.2}$ contrast ratio. Consequently, effective PSF suppression is also required for small inner working angles (IWAs). These effects make this type of observation prohibitively challenging from the ground, and it is clear that space-based instruments are required.

In addition to exoearths, there are binary or multiple star systems. Here the compelling question is with ***the binarity fraction of massive stars and the incidence of sub-stellar companions.*** There appears to be three times as many massive stars ($M > 2M_{\odot}$) in binary systems than that of stars with $0.1 < M_{\odot} < 2$. Could faint stars fall below detection limits set by bright stars and contrast ratios, or could this result come from the way multiple star systems form? Simple surveys of stellar systems could make significant progress on this question, and potentially (as a by-product) *find planetary systems, debris disks, and any faint nebulosity from pre- or post-main sequence evolution.*

There is also the question of ***the universality of the initial mass function.*** Ground-based studies struggle to detect a population of faint cooler low mass stars peaking in the IR, especially in extinguished systems that are close to the galactic plane. If there is a significant population of low mass companions to massive stars, could this change the form of the low mass end of the IMF?

Continuing, there is ***the characterization of circumstellar materials like remnant protostellar and secondary debris and exozodical light.*** An ECR survey would provide a new opportunity to closely study the end phases of pre-main sequence evolution, the proto-planetary environment, and the long-lived diffuse exozodi (that may be fed by collisions and cometary outgasing). Constraints on models of exoearth resonant signatures could also be made.

Finally, there is ***the relationship between nuclear activity and galaxy evolution***. Previous active galactic nuclei host studies have dealt with bright central sources (accreting supermassive black holes) by making less extreme contrast ratio observations. While studies have had some success in determining the properties of host galaxies, they use sophisticated techniques that rely on time intensive observations with HST.

TECHNICAL CAPABILITIES

- Spectral coverage: UV/visual to near-IR.
- Spectral resolving power, Angular resolution, Field of view: Can be budget limit driven.
- Primary operational mode: Survey.
- Sensitivity: Can be budget limit driven.
- Other important capabilities: Direct extreme contrast ratio imaging.

RELEVANCE OF THE FOUR MISSION CONCEPTS

There is a clear application for ECR technology onboard the Habitable-Exoplanet Imaging Mission and UV/Optical/IR Surveyor, and likely the Far Infrared Surveyor. All of these facilities could address the science questions posed.

NEW TECHNOLOGIES

In angular differential imaging the image plane is rotated with respects to the field due to an Alt-Az mounting. Objects within the field therefore rotate while the features of the PSF remain fixed. Therefore, such data can be combined to create a PSF model that is then removed from the original data. These data are then derotated and combined to produce a field in which the detrimental effects of a bright point source have been suppressed. In roll subtraction a difference image is created from data with the spacecraft at two roll angles. In this case the bright source subtracts out leaving other objects in the field. ***Roll differential imaging*** (RDI) combines both of these approaches. The spacecraft is orientated to at least three roll angles and the field imaged at each. A median-combined PSF model is then created, normalized, and divided out of the individual data frames. These frames are then combined in order to show other features in the field. Features that are stationary in the field would be highlighted in the median combined data, and features that have moved appear in the summed image. Consequently, future missions should include the ability to roll the spacecraft ~+/-15 degrees within a single visit, keeping the telescope fine-locked on a single pixel in the main imager that is placed at the principle optical axis in the field-of-view. This is a technique that is currently being quantified using HST archival data. We estimate this technique to be at TRL-6/7.

Separating the signals of relatively bright and faint targets is a significant challenge for standard MOS arrays because, in addition to the PSF suppression required, the directly achievable CRs are primarily determined by the full well depth of the pixels and limited to CR $< 10^5$. However, the latest generation charge-injection device (CID) are capable of directly producing ECRs $> 10^9$; the SpectraCAM XDR (SXDR). The detector consists of an array of X-Y addressable photosensitive MOS capacitor elements that are individually read out when they approach their full-wells. As a consequence they have an intrinsic 32-bit dynamic range. CIDs are currently at TRL-3, but should achieve TRL-7/8 during 2016 due to an ISS 2U NREP mission manifested for Space X-9 (CRS-9).

LARGE MISSION NEEDED?

A mission concept design study that includes RDI and CIDs is being proposed, but preliminary studies indicate a properly equipped 8-m monolithic Cassegrain design could meet the requirements of the key science questions above. This configuration could fit inside the oversized fairings of the future heavy lift launch vehicles. As this design is simple and uses high TRLs, the budget for such a mission could come in close to, or perhaps less than, $1B.

A FIR-Survey of TNOs and Related Bodies

J. M. Bauer[1,2], P. F. Goldsmith[1], C. M. Bradford[1], A. J. Lovell[3]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA; [2] Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA,USA; [3]Department of Physics and Astronomy, Agnes Scott College, Decatur, GA, USA

The small solar-system bodies that reside between 30 and 50 AU are referred to as the Trans Neptunian Objects, or TNOs. They comprise, in fact, the majority of small bodies within the solar system and are themselves a collection of dynamically variegated subpopulations, including Centaurs and Scatter-Disk Objects (SDOs), as well as "cold" (low-inclination and eccentricity) and "hot" (high eccentricity) classical Kuiper Belt populations (KBOs; Gladman et al. 2008). These minor planets are the reservoir of the comets that routinely visit our inner solar system, the short period comets, and so cloud the distinction between asteroids and comets. They are primordial material, unmodified by the evolution of the solar system and are the sources of volatile materials to the inner solar system (Barucci et al. 2008). Study of TNOs can thus inform us about the early history of the solar system, and how its composition has evolved over the time since it was formed.

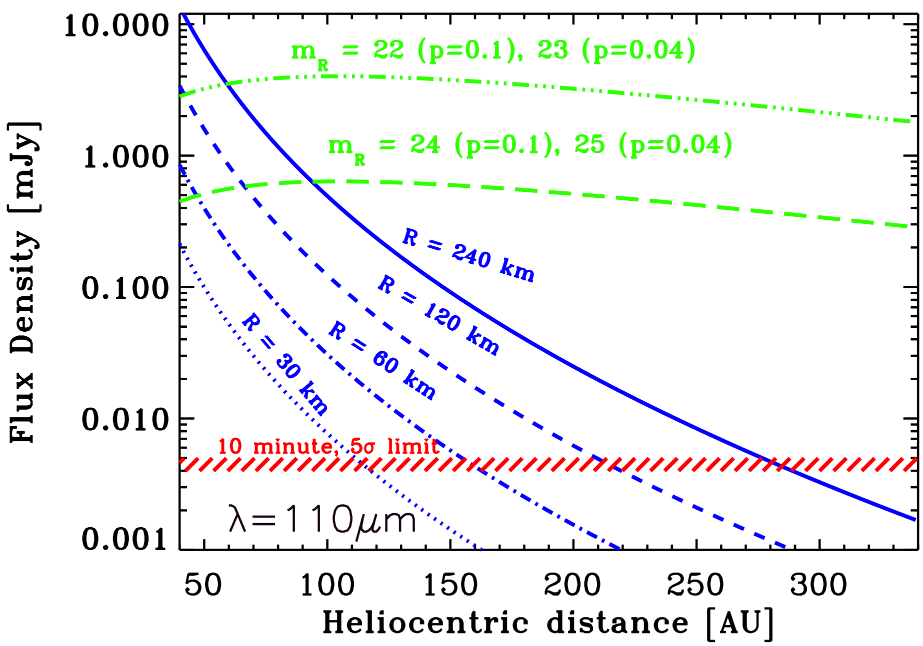


Figure 1: Flux density at 110 μm from TNOs of different radii (curves labeled by radius R) compared with CALISTO's 5σ detection limits for integration times of 10 min (diagonal-dashed horizontal line) The curves with indicated R-band (620 nm) magnitude m_R, and geometric albedo, p, give the flux from TNOs which are at limit of optical detectability. These lie well above the CALISTO limits.

A FIR TNO Survey: Surveys of these more distant solar system bodies to date are limited by optical-band sensitivities down to the 22-24 magnitude level (cf. Petit et al. 2011) and sizes in excess of 100 km (cf. Vilenius et al. 2012). Even The Large Synoptic Survey Telescope (LSST) will have a limiting magnitude near this range (m_R~24.5; LSST Science Book V2. 2009, p. 18). A far-infrared (FIR) mission with survey capabilities, like the prospective Cryogenic Aperture Large Infrared Space Telescope Observatory (CALISTO; Goldsmith et al. 2008), offers the potential for the first time of really probing the population of TNOs down to moderates sizes, and out to distances exceeding 100 AU from the Sun.

Orbital Resonances with Neptune pump up inclination in the KBOs. Beyond 100AU, the TNO population may flare out as well, with a larger dispersion in inclination, and an increase in the surface density of objects (Morbidelli & Brown 2004). The green curves in Figure 1 (labeled with value of m_R) give an idea of the flux density produced by TNOs which are at the limit of detectability at optical wavelengths. CALISTO evidently can go more than one order of magnitude below this, even with predicted confusion limits, indicating the advantage of high sensitivity submillimeter observations of TNO thermal emission, and may go fainter with repeated observations of the field when the object has moved off of background sources.

The ability to derive large quantities of size measurements is a unique value of such FIR surveys. Small bodies typically can vary in their surface reflectivity by factors of 5 or more, while surveys that detect emitted light provide reliable sizes from the flux (cf. Mainzer et al. 2011). This is important because the previous optical surveys have provided alternate size frequency distributions, based on inferences of reflectivity, indicative of competing evolution histories for these bodies (Trujillo et al. 2001; Bernstein et al. 2004; Schlichting et al. 2013), especially at the smaller end (TNO diameters <100 km) of the size scales. Objects at TNO distances will be best detected at wavelengths near 110 μm. Shorter (~50 μm), and longer (~200 μm), wavelengths will better constrain the sizes and temperatures of the objects observed.

Expected Populations: Presently, most surveys have placed order-of-magnitude constraints on larger TNOs, with solar-system absolute magnitudes (H)~9 and sizes ~100 km. Petit et al. (2011) place the total of all TNOs, mostly in the classical KBO population near the ecliptic plane, over 100 km in size at ~130,000 in number, and Scattered Disk Objects (SDOs) down to similar sizes, more widely distributed in orbital inclination, near 25,000 in number. Schlichting et al. (2013) and Trujillo et al. (2001) place a cumulative size frequency distribution exponent value q~4, where the number of bodies N with diameters > D go as:

$$N(> D) \propto D^{1-q}$$

so that if, as Figure 1 suggests, a CALISTO-type survey of $1/10^{th}$ of the sky is sensitive down to TNO diameters D~50 km or smaller, such a survey may yield several tens of thousands of new TNO discoveries, and a correspondingly large sample of TNO sizes, as well as thousands of new SDOs and diameters.

Related Activity in Related Populations: CALISTO also has the potential for detecting the limits of cometary activity in these and related populations. Species such as CO may drive sublimation out to distances of several tens of AU (Meech and Svoren, 2004). Detection of extended moving objects within a field owing to the presence of gas and dust coma is possible, and the expected size of such features would extend over several beam widths (A. J. Lovell, private communication). Such observations would place key constraints on the rates of mass lost to ejection of dust from these bodies, as well as the abundance of rarely-observed extremely-volatile species that may be relatively depleted in short-period comets (cf. Bauer et al. 2011, 2012). The onset of such distant activity may be linked to observational phenomenon heretofore unexplained, such as the source of the Centaur color bimodality (the red and gray sub-populations; Tegler et al. 2008), as well as place constraints on the primordial conditions under which they were formed.

References:

Barucci, M. A., H. Boehnhardt, D. P. Cruikshank, & A. Morbidelli 2008, in The Solar System Beyond Neptune: Overview and Perspective, ed. M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 3.

Bauer, J. M., Walker, R. G., Mainzer, A. K., et al. 2011. WISE/NEOWISE Observations of Comet 103P/Hartley 2. ApJ, 738, 171.

Bauer, J. M., Kramer, E. Mainzer, A. K., et al. 2012. WISE/NEOWISE Preliminary Analysis and Highlights of the 67P/Churyumov-Gerasimenko near Nucleus Environs. ApJ, 758, 18.

Bernstein, G. M. D. E. Trilling, R. L Allen, et al. 2004. The Size Distribution of Trans-Neptunian Bodies, AJ 128, 1364.

Gladman, B., B. G. Marsden, and C. VanLaerhoven 2008, in The Solar System Beyond Neptune, Nomenclature in the Outer Solar System, ed. M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 43.

Goldsmith, P. F., M. Bradford, M. Dragovan, C. Paine, C. Satter, et al. "CALISTO: the Cryogenic Aperture Large Infrared Space Telescope Observatory", Proc. SPIE 7010, Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter, 701020 (July 12, 2008); doi:10.1117/12.788412

Mainzer et al. 2011. NEOWISE Observations of Near-Earth Objects: Preliminary Results. ApJ. 743, 156.

Meech, K. J., and J. Svoren. 2004. in Comets II, Using Cometary Activity toTrace the Physical and Chemical Evolution of Cometary Nuclei, ed. M. C.Festou et al. (Tucson, AZ: Univ. Arizona), 317.

Morbidelli, A. and M. E. Brown. 2004. in Comets II, The kuiper belt and the primordial evolution of the solar system, ed. M. C.Festou et al. (Tucson, AZ: Univ. Arizona), 175.

Petit, J.-M., J. J. Kavelaars, B. J. Gladman, R. L. Jones, J. Wm. Parker, C. Van Laerhoven, P. Nicholson, G. Mars, P. Rousselot, O. Mousis, B. Marsden, A. Bieryla, M. Taylor, M. L. N. Ashby, P. Benavidez, A. Campo Bagatin, and G. Bernabeu. 2011. The Canada France Ecliptic Survey – Full Data Release: The Orbital Structure of the Kuiper Belt. Astron. J. 142, 131.

Schlichting, H. E., C. I Fuentes, and D. E. Trilling. 2013. Initial Planetesimal Sizes and the Size Distribution of Small Kuiper Belt Objects. AJ 146, 36.

Tegler, S. C., J. M. Bauer, W. Romanishin, and N. Peixinho. 2008, in The Solar System Beyond Neptune, Colors of Centaurs, ed. M. A. Barucci, H. Boehnhardt, D. P. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 105.

Trujillo, C. A., D. C. Jewitt, and J. X. Luu, 2001. Properties of the Trans-Neptunian Belt: Statistics from the Canada-France-Hawaii Telescope Survey. AJ 122, 457.

Vilenius, E., C. Kiss, M. Mommert, T. Müller, P. Santos-Sanz, et al. 2012. “TNOs are Cool”: A survey of the trans-Neptuneian region, VI. Herschel⋆/PACS observations and thermal modeling of 19 classical Kuiper belt objects. Astron. & Astroph. 541, A94.

Unlocking the Secrets of Planet Formation with Hydrogen Deuteride

Edwin A. Bergin (University of Michigan)

The following is a white paper that discusses how a far-IR observatory, with significant gains in sensitivity over Herschel, could make a major contribution towards our understanding of the physics of planet formation and the birth of habitable worlds.

The Uncertain Gas Mass of Planet-Forming Disks

Planets are born within disk systems (protoplanetary disks) that are predominantly molecular in composition with a population of small (sub-micron to cm sized) dust grains that represent the seeds of Earth-like planets. The most fundamental quantity that determines whether planets can form is the protoplanetary disk mass; forming planetary systems like our own requires a minimum disk mass of order $\sim$0.01 $M_\odot$ (i.e. the minimum mass solar nebula or MMSN; Weidenschilling, 1977; Hayashi, 1981). Estimates of disk masses are complicated by the fact that the molecular properties of dominant constituent, molecular hydrogen, lead it to be unemissive at temperatures of 10 – 30 K that characterizes much of the disk mass (Carmona et al., 2008).

To counter this difficulty astronomers adopt trace constituents as proxies to derive the H_2 mass. By far, the primary method is to use thermal continuum emission of the dust grains. At longer sub-mm/mm wavelengths the dust emission is optically thin probing the disk dust mass. With an assumed dust opacity coefficient, along with the ratio of the dust to gas mass, the disk gas mass is determined from the dust mass (Beckwith et al., 1990; Andrews & Williams, 2005). With this method the gas mass estimates range from $5 \times 10^{-4} - 0.1$ $M_\odot$ (Williams & Cieza, 2011). However, a variety of sensitive observations have demonstrated that grains have likely undergone growth to sizes 1 mm to 1 cm (at least) in many systems (Testi et al., 2014). Thus the dust opacity is uncertain and the gas-to-dust ratio is likely variable (Draine, 2006; Isella et al., 2010). The alternative is to use rotational CO lines as gas tracers, but these are optically thick, and therefore trace the disk surface temperature, as opposed to the midplane mass. The use of CO as a gas tracer then leads to large discrepancies between mass estimates for different models of TW Hydrae, the closest gas-rich disk (from 5×10^{-4} $M_\odot$ to 0.06 $M_\odot$), even though each matches a similar set of observations (Thi et al., 2010; Gorti et al., 2011).

These uncertainties are well known with broad implications regarding the lifetime where gas is available to form giant planets, the primary mode of giant planet formation, either core accretion or gravitational instability in a massive disk (Hartmann, 2008), on the dynamical evolution of the seeds of terrestrial worlds (Kominami & Ida, 2004; Ida & Lin, 2004), and the resulting chemical composition of pre-planetary embroyos (Öberg et al., 2011). Given current uncertainties, we do not know whether our own solar system formed within a typical disk (Williams & Cieza, 2011). This extends beyond our planetary system as the frequency of extra-solar planet detections has been argued to require higher disk masses (Greaves & Rice, 2010; Mordasini et al., 2012).

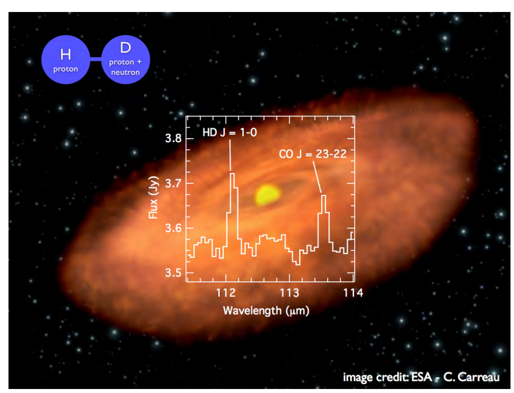


Figure 1: Herschel detection of Hydrogen Deuteride in the TW Hya protoplanetary disk superposed on an artist conception of a young gas-rich disk.

Far-IR Spectroscopy, HD, and Disk Gas Masses

Bergin et al. (2013), using the Herschel Space Observatory, detected the fundamental rotation transition of HD at 112 μm emitting from the TW Hya disk (shown in Fig. 1). The atomic deuterium abundance relative to H_2 is well characterized to be $3.0\pm0.2\times10^{-5}$ in objects that reside within $\sim$ 100 pc of the Sun (Linsky, 1998), such as TW Hydra. Unlike carbon monoxide, HD and H_2 are only weakly bound on the cold (T $\sim$ 10 – 20 K) dust grains that reside in the mass carrying disk midplane (Tielens, 1983). Thus HD resides primarily in the gas throughout the disk with a known abundance relative to H_2. With energy spacings better matched to the gas temperature and a weak dipole the lowest rotational transition of HD is a million times more emissive than H_2 for a given gas mass at 20 K. It is therefore well calibrated for conversion of its emission to the H_2 gas mass in the disk offering the best chance to derive accurate disk gas masses in regions that are potentially actively forming planets. In the case of TW Hya the gas mass is estimated to be > 0.05 $M_\odot$, or many times the MMSN.

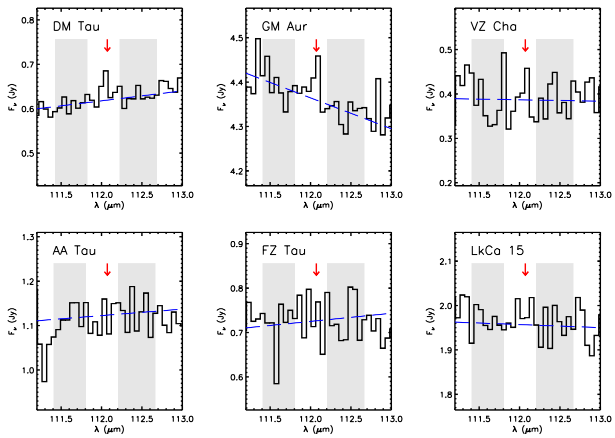


Figure 2: Results from the shallow survey of HD emission to be published by McClure et al. 2015, in prep.

Due to Herschel's limited lifetime the only other deep HD observations were obtained in the Cycle 1 program that resulted in the TW Hya detection. These observations, which are less sensitive than the TW Hya data, are shown in Fig. 2. For the most part, at this sensitivity limit, HD was not detected, although these disk are $\sim$3$\times$ more distant than TW Hya. However, marginal detections ($> 3\sigma$) were obtained in DM Tau and GM Aur hinting at the future promise for a high impact survey with a future far-IR facility.

A survey of HD emission, can only be enabled with a sensitive Far-IR observatory. To move beyond the $\sim$ 3 systems with accurate gas masses, and open up our understanding of planet formation, we need to detections in $>$ 100 disk systems. This will provide the missing - and grounding - information on the gas masses of planet-forming disks. Such a survey of a hundred of the nearest systems can determine the timescales of planet formation, whether H_2 is present in debris disk systems, and set needed constraints for disk dynamical models. A large telescope might also *resolve* HD in the closest systems, allowing for constraints to be placed on the uncertain gas density profile.

Knowledge of the disk mass also breaks the degeneracy between disk mass and chemical abundance. As an example, Favre et al. (2013) used HD with $C^{18}O$ finding that the CO abundance is more than an order of magnitude below that in the dense ISM. This was explored more directly (Du, Bergin, and Hogerheijde 2015, in prep.) using a complete thermochemical model (Du & Bergin, 2014) to analyze CO isotopologue data but also Spitzer/Herschel observations of water vapor. This work finds that to match observations, the abundance of elemental oxygen and carbon must be reduced in the upper layers by orders of magnitude. This missing carbon and oxygen must reside as ices in the dense midplane locked inside pebbles or even planetesimals. This information is crucial as the Atacama Large Millimeter Array is now providing resolved images of gas tracers, such as CO and other species. Without HD in TW Hya we would assume that readily accessible gas tracers (e.g. CO, HCN, etc) suggest that the gas mass is low, while instead it is the beginnings of planet formation that is being revealed. Thus there is tremendous synergy of a future far-IR facility with ground based instruments; only the far-IR can provide this fundamental information.

References

Andrews, S. M. & Williams, J. P. 2005, Astrophys. J. , 631, 1134

Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, Astron. J. , 99, 924

Bergin, E. A., Cleeves, L. I., Gorti, U., Zhang, K., Blake, G. A., Green, J. D., Andrews, S. M., Evans, II, N. J., Henning, T., Öberg, K., Pontoppidan, K., Qi, C., Salyk, C., & van Dishoeck, E. F. 2013, Nature , 493, 644

Carmona, A., van den Ancker, M. E., Henning, T., Pavlyuchenkov, Y., Dullemond, C. P., Goto, M., Thi, W. F., Bouwman, J., & Waters, L. B. F. M. 2008, Astron. & Astrophys. , 477, 839

Draine, B. T. 2006, Astrophys. J. , 636, 1114

Du, F. & Bergin, E. A. 2014, Astrophys. J. , 792, 2

Favre, C., Cleeves, L. I., Bergin, E. A., Qi, C., & Blake, G. A. 2013, Astrophys. J. Letters , 776, L38

Gorti, U., Hollenbach, D., Najita, J., & Pascucci, I. 2011, Astrophys. J. , 735, 90

Greaves, J. S. & Rice, W. K. M. 2010, MNRAS , 407, 1981

Hartmann, L. 2008, Physica Scripta Volume T, 130, 014012

Hayashi, C. 1981, Progress of Theoretical Physics Supplement, 70, 35

Ida, S. & Lin, D. N. C. 2004, Astrophys. J. , 604, 388

Isella, A., Carpenter, J. M., & Sargent, A. I. 2010, Astrophys. J. , 714, 1746

Kominami, J. & Ida, S. 2004, Icarus , 167, 231

Linsky, J. L. 1998, Space Sci. Rev., 84, 285

Mordasini, C., Alibert, Y., Benz, W., Klahr, H., & Henning, T. 2012, Astron. & Astrophys. , 541, A97

Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, Astrophys. J. Letters , 743, L16

Testi, L., Birnstiel, T., Ricci, L., Andrews, S., Blum, J., Carpenter, J., Dominik, C., Isella, A., Natta, A., Williams, J. P., & Wilner, D. J. 2014, Protostars and Planets VI, 339

Thi, W.-F., Mathews, G., Ménard, F., Woitke, P., Meeus, G., Riviere-Marichalar, P., Pinte, C., Howard, C. D., Roberge, A., Sandell, G., Pascucci, I., Riaz, B., Grady, C. A., Dent, W. R. F., Kamp, I., Duchêne, G., Augereau, J.-C., Pantin, E., Vandenbussche, B., Tilling, I., Williams, J. P., Eiroa, C., Barrado, D., Alacid, J. M., Andrews, S., Ardila, D. R., Aresu, G., Brittain, S., Ciardi, D. R., Danchi, W., Fedele, D., de Gregorio-Monsalvo, I., Heras, A., Huelamo, N., Krivov, A., Lebreton, J., Liseau, R., Martin-Zaidi, C., Mendigutía, I., Montesinos, B., Mora, A., Morales-Calderon, M., Nomura, H., Phillips, N., Podio, L., Poelman, D. R., Ramsay, S., Rice, K., Solano, E., Walker, H., White, G. J., & Wright, G. 2010, Astron. & Astrophys. , 518, 647

Tielens, A. G. G. M. 1983, Astron. & Astrophys. , 119, 177

Weidenschilling, S. J. 1977, MNRAS , 180, 57

Williams, J. P. & Cieza, L. A. 2011, Ann. Rev. Astron. Astrophys. , 49, 67

A Cryogenic Telescope for Far-Infrared Astrophysics: A Vision for NASA in the 2020 Decade

C.M. Bradford[1] and others

May 11, 2015

see full document at: `http://conference.ipac.caltech.edu/firsurveyor/page/documents`

Abstract

The Far-IR Science Interest Group will meet from 3–5 June 2015[2] with the intention of reaching consensus on the architecture for the Far-IR Surveyor mission. This paper is an except from a larger document which describes one of the architectures to be considered by the community. We present the Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory (CALISTO), a 5-meter class, space-borne telescope actively cooled to T$\sim$4 K, emphasizing moderate-resolution spectroscopy in the crucial 35 to 600 μm band. CALISTO will enable NASA and the world to study the rise of heavy elements in the Universe's in the first billion years, chart star formation and black hole growth in dust-obscured galaxies through cosmic time, and conduct a census of forming planetary systems in our region of the Galaxy. CALISTO will capitalize on rapid progress in both format and sensitivity of far-IR detectors. Arrays with a total count of a few $\times 10^5$ detector pixels will form the heart of a suite of moderate-resolution (R$\sim$500–1000) imaging spectrometers in which each detector reaches the photon background limit. Other instruments are also under consideration, including broad-band imagers and high-spectral-resolution (R>10,000) spectrometers.

1 Motivation for Sensitive Wideband Far-IR Spectroscopy

The sensitive CALISTO platform is especially compelling for wideband spectroscopy, as Figure 1 shows and Table 2 presents. CALISTO will obtain full-band spectra of thousands of objects ranging from the first dusty galaxies to the most heavily enshrouded young stars and proto- planetary disks in our own Galaxy, as well as blind discovery of thousands more. These CALISTO spectra will directly address several key goals of modern astrophysics:

- Measure the onset of heavy elements and the rise of organic molecules in the Reionization Epoch. See white papers by Cooray et al., and Appleton et al. for more information.
- Chart the true history of cosmic star formation and its connection to supermassive black hole growth. More information can be found in a white paper by Armus et al.
- Measure clustering and total emission of faint galaxies below the individual detection threshold using tomographic intensity mapping of the far-IR emission lines.
- Probe the cycling of matter and energy in the Milky Way and nearby galaxies.
- Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence. A white paper by Bergin et al. describes this more fully.

2 Architecture Choice

The scientific goals outlined above require excellent spectroscopic sensitivity, both for point sources and mapping, with full coverage between the 28 μm cutoff of JWST MIRI and the onset of the ground-based windows at $\sim$600 μm. Accessing the earliest galaxies and most-evolved lowest-mass protoplanetary systems requires a line sensitivity below $10^{-20}\,\mathrm{W\,m^{-2}}$, large instantaneous bandwidth, and moderate spectral resolving power ($R = \delta\lambda/\lambda \geq 500$). The requirement for ultimate sensitivity demands maximum collecting area, low telescope background, and high efficiency. Blind spectroscopic surveys over large fields will also be a part of the program, so the observatory must have enough throughput (AΩ) to make use the large-format array technology now available. These crucial attributes are summarized in Table 1. Collecting area per unit cost is maximized with a monolithic-aperture telescope, particularly since the entire telescope and instruments will be actively cooled.

[1]JPL and Caltech, `bradford@caltech.edu`

[2]`http://conference.ipac.caltech.edu/firsurveyor/`

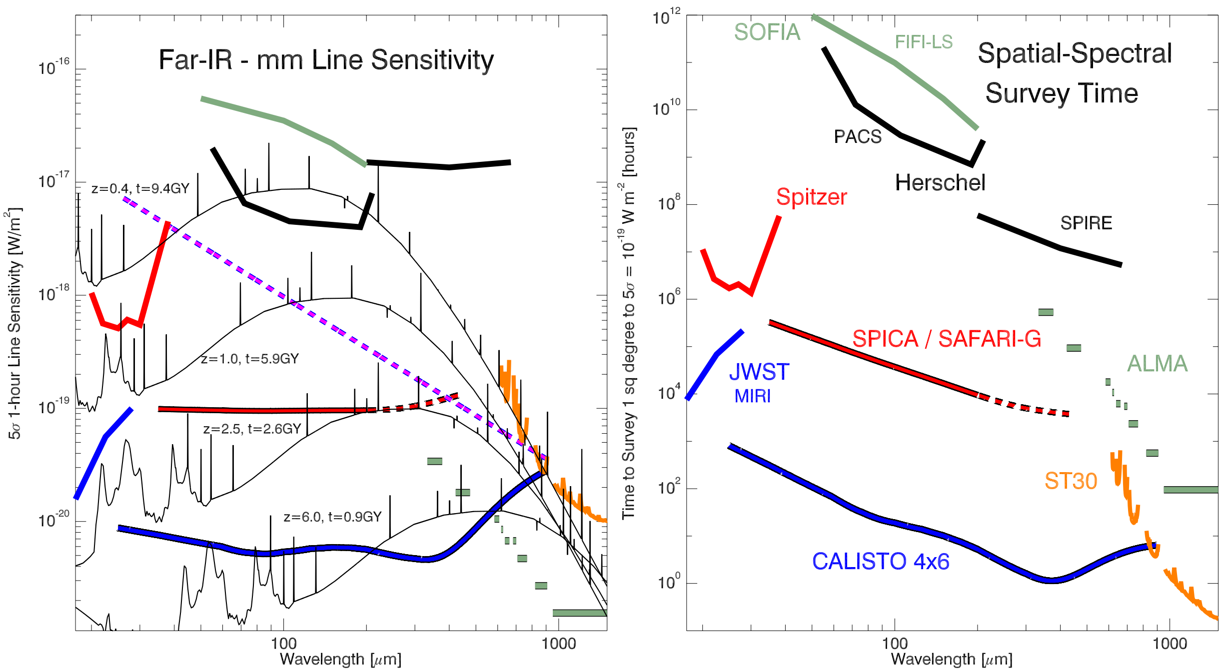


Figure 1: Spectroscopic sensitivities in the far-IR and submillimeter. Left shows the sensitivity in $\mathrm{W\,m^{-2}}$ for a single pointed observation. Galaxy spectra assuming $L = 10^{12}\,L_\odot$ at various redshifts are overplotted using light curves, with continuum smoothed to R=500. The magenta dashed line shows the sensitivity of a quantum-limited heterodyne receiver (T_{sys}=hν/k) in a bandwidth of 10 km/s. The right panel shows the speed for a blind spatial-spectral survey reaching a depth of $10^{-19}\,\mathrm{W\,m^{-2}}$ over a square degree, including the number of spatial beams and the instantaneous bandwidth. For more information see the full document.

Cooling all parts of the telescope and instrument environment to a few degrees K is essential for the excellent sensitivity, and this is a firm requirement for CALISTO. Cooling will be provided by closed-cycle helium coolers, carefully integrated into a passive cooling architecture which uses staged V-groove radiators. 4-K class spaceflight coolers have been developed by industries worldwide, and the effectiveness of the V-groove system has been demonstrated with the ESA Planck telescope, which reached below 40 K on orbit.

The telescope design is a topic for study. An example configuration for the telescope is our point design described in Goldsmith et al., 2008 [**?**], and shown in Figure 2. This design features a 4×6-meter monolithic primary mirror used off-axis, and a secondary mirror which is deployed with a single hinge mechanism. This provides an optimal collecting area in a non-deployed primary mirror which fits into a 5-m fairing. While other materials could be considered, a promising approach is to use silicon carbide (SiC), which is attractive given its favorable thermomechanical properties, and given it's success in the Herschel observatory, a system with comparable size and surface accuracy requirements to CALISTO. Other aspects are less clear, and there are several inter-related design choices that we propose to consider in a study prior to the Astro2020 submission including: on-axis vs. off axis, segmented vs. monolithic primary, active (correctable on orbit) vs passive primary, and cost scaling with the primary mirror size.

The approaches for the grating-type spectrometers and the large arrays of frequency-domain-multiplexed supercon-

Table 1: CALISTO Basic Parameters

Parameter	Value
Telescope Temperature	<4 K
Telescope Diameter	∼5 m
Telescope Surface Accuracy	1 μm
Telescope Field of View	1 deg at 500 μm
Instrument Temperature	50–100 mK
Total Number of Detectors	1–5×10^5
Heat Lift at 4 K	∼150 mW
Heat Lift at 20 K	∼2 W
Data Rate	∼ 1 Gbit / sec

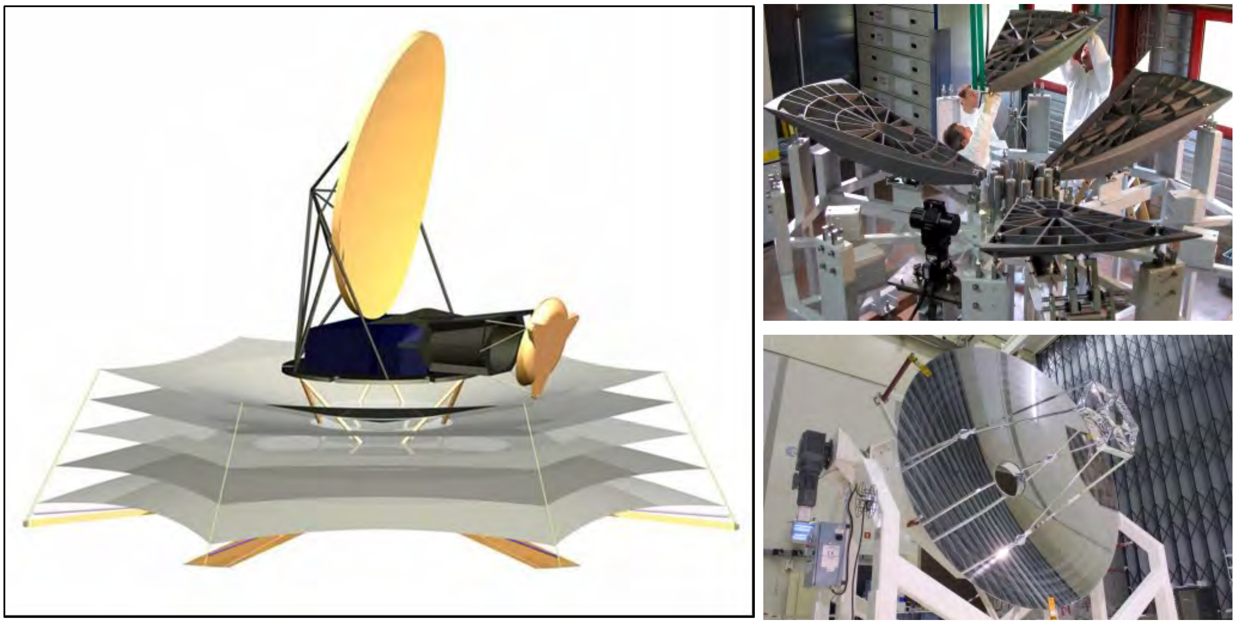


Figure 2: Left: CALISTO concept. 5-meter class telescope is actively cooled with closed-cycle coolers to $\sim$4 K. Passive and active cooling are integrated in a design which features V-groove radiators as used on Planck and JWST. Right: Large cold telescope heritage: the 3.5-meter Herschel silicon carbide primary mirror, prior to assembly from 8 petals and figuring, and as integrated into the telescope. Other mirror approaches will also be considered.

ducting direct detector arrays are described in the main document. The envisioned capabilities are shown in Figure 1 and Table 2. In addition, we emphasize that a single-dish telescope also naturally accommodates a wide range of other potential instrumentation, for example broadband imaging arrays, heterodyne receiver arrays, and 2-D imaging spectrometers such as Fabry-Perot interferometers. In particular, broadband imaging at 100 μm will be particularly powerful with CALISTO (see white paper by Caitlin Casey), and a modest 4000-pixel camera can yield an all sky survey with an angular resolution of 5$''$.

3 Cost Landscape

CALISTO was studied by JPL Team-X in various exercises between 2005 to 2008. The telescope configuration described above, the associated cryocoolers, the deployed sunshade, an allocation for instruments, and operations for a 5-years mission were estimated to cost \$1.7 billion (FY2008\$). Re-assessing this is an important aspect of our proposed pre-decadal study. One key point is that we are now advocating substantially more capable instrumentation for CALISTO. While the new frequency-domain multiplexing schemes naturally enable the large formats, we nevertheless expect that the increased scope will increase both the instrument and science terms in the budget (over the full mission life) relative to the 2008 estimate. On the other hand, much of the science can be retained with a reduction in aperture, so that is a means to reduce cost.

Table 2: CALISTO Spectrometer Backends: R=500 Strawman Design

Parameter	40 μm	120 μm	400 μm	Scaling w/ $D_{\rm eff}$
Dominant background	zodi dust	zodi. + gal. dust	tel. + CMB	...
Photon-noise limited NEP [$\rm W\,Hz^{-1/2}$]	3e-20	3e-20	4e-20	...
Beam size	1.9$''$	5.9$''$	19$''$	$\propto D^{-1}$
Instantaneous FOV [sq deg]	4.0e-5	3.8e-4	2.3e-3	$\propto D^{-2}$
Line sensitivity $\rm W\,m^{-2}$, 5σ, 1h	4.2e-21	3.3e-21	3.2e-21	$\propto D^{-2}$
Pt. sce. mapping speed [$\rm deg^2/(10^{-19}W\,m^{-2})^2/sec$]	1.6e-4	2.4e-3	1.6e-2	$\propto D^{2}$
Surface bright. sens. per pix [MJy/sr $\sqrt{\rm sec}$]	4.2	1.1	0.33	$\propto D^{0}$

Notes: Sensitivities assume single-polarization instruments with a product of cold transmission and detector efficiency of 0.25 in a single polarization, and an aperture efficiency of 0.75. FOV estimate assume slit widths of 165 λ/D for the 40 and 120 μm examples, and 100 individual single-beam spectrometer backends for the 400 μm case.

Imaging Polarimetry for ExoPlanet science & astrophysics

James B. Breckinridge
jbreckin@caltech.edu

1. Key science questions

Polarization measurements of astronomical sources in the UVOIR contain substantial astrophysical information on star formation & evolution, interstellar medium, and gas cloud dynamics. The asymmetry of aligned dipoles in interstellar matter selectively absorb the thermal emission from background stars to reveal the presence of magnetic fields and their anomalies in the galaxy and in the neighborhood of stars[1]. Unpolarized radiation that scatters from planetary atmospheres and circumstellar disks becomes partially polarized to reveal structural dynamics, chemistry, aerosols, and surface features. The value of precision imaging polarization measurements to general astrophysics is well known across the UVOIR region[2,3].

Data from the imaging photopolarimeters on Pioneers 10 and 11 and the Voyagers showed that Jupiter-like exoplanets will exhibit a degree of polarization (*DoP*) as high as 50% at a planetary phase angle near 90°. Polarization measurements of the planet's radiation in the presence of light scattered from the star reveals the presence of exoplanetary objects and provides important information on their nature. de Kok, Stam & Karalidi (2012) showed that the *DoP* changes with wavelength across the UV, visible and near IR band-passes to reveal the structure of the exoplanet's atmosphere.

Several theoretical models[4,5] show that the *degree of polarization* changes with wavelength across the UV, visible and near IR band-passes to reveal the structure of the exoplanet's atmosphere, its climate and even details of the orbital elements of the exoplanet system[6].

Polarimetric imaging of exoplanets has the potential to reveal important details of atmospheric composition, radiative transfer, aerosol & chemical composition, cloud-cover, and surface composition. Polarimetric imaging reveals important information about grain sizes in protoplanetary dust clouds, and their role in planet formation. Contrast sufficient for terrestrial exoplanet imaging requires polarization control[7,8].

Much work has been done to calibrate telescopes for the radiometric measurement: photo-polarimetry, by treating the telescope and imaging system as neutral density filter whose transmittance depends on the sky position. The role of polarization in the image formation process and the control of unwanted radiation is new[7].

Polarimetric imaging of astronomical sources provide critical astrophysical and exoplanet information. All polarization measurements are made with telescopes and instruments that contribute their own polarization signature, which is, in some cases larger than the polarizance of the astronomical source. Internal polarization changes the shape of the image. Light spills out around the focal plane mask to flood the coronagraph with unwanted radiation.

2. Technical capabilities

To observe physical phenomena across the bandwidth 100 to 5,000 nm several new technical capabilities are needed. These are: 1. Control of scattered light to 1:1E10 contrast; 2. Coronagraph/telescope internal polarizance < 0.01%; 3. Integration times of 10 hours with 0.001 arc second stability. 4. Photon counting high dynamic range detector; 5. Low spatial resolution (~256x256), R~70 spectrometer; 5, greater than thirty-meter squared collecting area; 6. Twelve-meter baseline aperture; 7. A UVOIR optical system with end-to-end transmittance of >10%; 8. Cost effective technical system architecture.

---

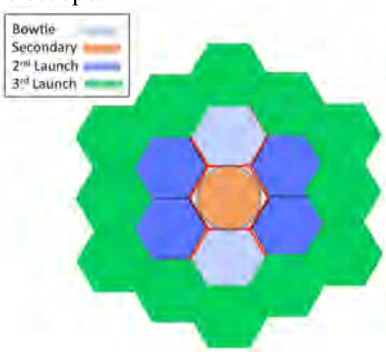
[1] Mavko, G. E., Hayes, D. S.,Greenberg, J. M. & Hiltner, W. A. 1974, ApJ, 187, L117
[2] Clarke, D. 2010, Stellar Polarimetry, Wiley
[3] Perrin, M. D., et al. 2009a, ApJ, 707, L132
[4] de Kok, R. J., Stam, D. M., & Karalidi, T. 2012, ApJ, 741, 59
[5] Madhusudhan, N. & Burrows, A. 2012, ApJ, 747, 25
[6] Fluri, D. M. & Berdyugina, S. V. 2010, A&A, 512, A59
[7] Breckinridge, J. B., W. T. Lam and R. A. Chipman (2015) Publ. Astron. Soc. Pacific, **127**, May
[8] Breckinridge, J. B. and B. R. Oppenheimer (2004) ApJ **600**:1091-1098

3. Relevance of the four mission concepts

Precision high angular resolution imaging and coronagraphy is of most interest to the ultraviolet, optical and infrared (UVOIR) communities and the Habitable-Exoplanet Imaging Mission. The angular resolution of the Far-IR surveyor will be insufficient. To be cost effective the UVOIR and the Habitable-Exoplanet Imaging system need to use the evolvable space telescope (EST) concept, which requires several new technologies discussed below.

4. New Technologies

A minimum number of new technologies are needed to implement the EST for the UVOIR and the Habitable-Exoplanet Imaging Mission. Table 1 describes the engineering concept and the technical capabilities of each of the three stages of a space telescope that would be developed, launched, assembled and operated in the 2030's and beyond. The first Stage telescope would consist of two ~4-m hexagonal mirror segments, a prime focus instrument module and a support structure to separate the instruments from the primary mirror. A sunshield would provide thermal protection for the telescope, and a spacecraft bus would provide the necessary power, communications and attitude control. Stage 2 and Stage 3 components are robotically docked, in cis-lunar space or at L2, in a fashion similar to that commonly used by the space station. At each stage the optical structure is then autonomously aligned to form a working optical telescope.



Parameter	Requirement	Goal	Notes
Telescope Aperture	≥ 10 meters	≥ 16 meters	≥ ATLAST
Stage 1	Bow-tie	4 x 12 m	Two hexagonal segments
Stage 2	Filled Aperture	12 m	Twelve hexagonal segments
Stage 3	Filled Aperture	20 m	Eighteen hexagonal segments
Wavelength	100-2400 nm	0.09-670 μ	UVOIR, Far-IR under evaluation
Field of View	5 to 8 arcmin	30 arc-min	Wide Field VNIR Imaging
Diffraction Limit	500 nm	200 nm	Enhanced UV/Optical resolution
Primary Segment Size	1.97 m	3.93 m	3.93m flat-flat
Primary Mirror Temp	≤ 200K	100K	Minimize heater powe, MIR obs.
Design Lifetime	15 years	> 30 years	On-orbit assembly and servicing

Stage 1 of the EST has a 4 x 12 meter sparse aperture primary mirror and a prime focus instrument module with room for instruments: a wide field camera for the UVOIR, an exoplanet coronagraph, and a UV spectrometer. Prime focus instruments have the very high transmittance and very low residual polarization characteristic of optical systems with few fold mirrors and near-normal incidence optics that reduce the presence of the unwanted ghost images. The instrument complement for each stage would depend on the science drivers that could be best addressed with 12 x 4-m sparse aperture, a 12-m filled aperture, and a 20-m filled aperture. Note, the Stage 1 telescope can be rotated around its line of sight, and images acquired at roll angles of 0, 60 and 120 degrees can be combined to achieve the spatial resolution of a 12-m filled aperture.

The spatial resolution of the Stage-1 and Stage-2 telescopes will thus range from 20 to 100 mill-arc-seconds for the near IR (0.9 to 5 μ), 6 to 20 mas for the Visible (0.3 to 0.9 μ) and 1.9 to 6.3 mas for the UV instruments (0.09 - 0.35μ). The resolution of the Stage 3, 20-m EST will be 40% better than Stage 2. We currently envision the installing a larger sunshield for the Stage 3 20-m telescope. Specifically, new technologies in these areas will be required: Low intrinsic polarization and tilt compensated telescope and instrument designs, High dynamic range photon counting detectors, Image plane masks and Lyot stops optimized for full vector complex amplitude and phase wavefronts, Low polarization coatings, Vibration and thermal control optimized for coronagraphy, Innovative coronagraph concepts, design, breadboard test and development, Self-assembly of telescopes in space and autonomous alignment and control, A cost-effective large space telescope followed by an instrument with minimum number of reflections each with the smallest possible angle of reflection is needed.

5. Large mission needed

A large mission is needed to obtain the needed high angular resolution and large collecting area to obtain the needed SNR, particularly for exoplanets at $m_V<32$.

– Dust in Distant Galaxies –
Overcoming Confusion Noise with a 5m FIR Facility

Caitlin Casey, Matt Bradford, Asantha Cooray, James Aguirre, Phil Appleton, Phil Mauskopf, Bade Uzgil

The vast majority of galaxy evolution studies in the past fifty years have focused on deep optical and near-infrared ($\lambda < 5\mu m$) datasets, tracing galaxies direct emission from starlight. Yet half of all energy emanating from these galaxies is emitted in the far-infrared and submillimeter, where dust and gas emit[1,2]. Dust absorbs emission from young, hot stars and re-radiates that energy at long wavelengths, peaking at rest-frame $\approx$100μm. This dust emission provides very important clues to galaxies' evolutionary history, but is virtually unconstrained observationally over the majority of the Universe's evolution and in normal, Milky Way type galaxies.

Previous limitations in far-infrared instrumentation and the atmospheric opacity at these wavelengths has made detailed studies of dust in distant galaxies extremely challenging in the past, with only a handful of missions successfully surveying the sky in the past thirty years. These include the *IRAS*[3] (1983) and *ISO*[4] (1995) missions, and in more recent history *Spitzer*[5] (2003), *AKARI*[6] (2006), and *Herschel*[7,8] (2009). However, these missions were all significantly limited by a combination of limited sensitivity and small apertures, thus large beamsizes and confusion noise. While improving on detector sensitivity has been quite successful in the past few decades, overcoming confusion noise has been difficult.

Here we outline the impact that a 5m space-borne FIR facility would have on the direct detection of dust in distant galaxies at $\approx$50–200μm. With a relatively modest increase in aperture size, the confusion-limited depth is vastly increased over that of the *Herschel Space Observatory*. This is a simple consequence of the fact that at these frequencies, the 5-meter class aperture is reaching below the knee in the luminosity function, and the shallow faint-end slope translates to a rapid increase in depth with decreasing beam size.

Confusion noise arises when the density of sources on the sky is high relative to the beamsize of observations. Overcoming confusion noise is difficult without a large aperture. For example, the *Herschel* PACS and SPIRE instruments (operating at 70–160μm and 250–500μm, respectively) were confusion limited such that integrating for long periods of time would not improve the depth of the instruments surveys because the resolution was not sufficient to distinguish sources from one another. Strictly speaking, the confusion limit for a given facility, $\mathrm{S_{conf}}$, is the limiting flux density for which $\Omega_{\rm beam} \times N(> S_{\rm conf}) = 1$, where $\Omega_{\rm beam}$ is the solid angle of one beam (in deg^{-2}) and $N(> S_{\rm conf})$ is the density of sources at or above $S_{\rm conf}$ at the given wavelength. Confusion noise will dominate for sources with fluxes fainter than $S_{\rm conf}$, where there are more than one source per beam. Another commonly used qualification of confusion noise, used to derive confusion noise in existing observational datasets[9], defines $\mathrm{S_{conf}}$ as $\int_0^{x_c} x^2\,dn$, where x is the measured flux, $x = S\,f(\theta,\phi)$, S is the source flux convolved with the normalized beam response, $f(\theta,\phi)$, and dn is the differential source distribution. In both cases, it is clear that the beamsize is the primary limitation in conducting very sensitive, deep FIR surveys.

Figure 1 illustrates the best measured differential number counts[10] at 70μm (from *Spitzer* MIPS[11,12] and *Herschel* PACS[13]), 100μm (from ISOPHOT[14,15,16] and *Herschel* PACS[13,17]) and 250μm (from BLAST[18,19] and *Herschel* SPIRE[20,21,22]). The differential number counts represent the number of sources per flux bin per area, plotted here in units of dN/dS [mJy^{-1} deg^{-2}], and is often fit to a parametric double power law or Schechter function, although it should be noted that such parametrizations are physically meaningless, as flux density is a function of luminosity, redshift and SED shape (dust emissivity, opacity, temperature, etc). Here we have overplot some best-fit double power law parametrizations, which extend to very low flux densities well below the limit of past FIR surveys. We have designated uncertainty on the faint end slope, α, of the number counts to mirror the uncertainty in the data in that regime.

The right panels on Figure 1 show the cumulative number counts in units of sources per beam. For each panel, the left y-axis represents the beamsize of a proposed 5m FIR facility, while the right y-axis represents the beamsize of *Herschel*, a 3.5m facility. Solid horizontal lines illustrate the $S_{\rm conf}$ limit of one source per beam, as per the formal definition of confusion noise, while the dotted lines represent a more practical confusion limit of $^1/_4$ source per beam, in line with measured confusion limits from *Herschel* (note this value will depend strongly on the clustering of galaxies, which differs by wavelength). **What this shows us is that a beamsize that is reduced by a factor of ∼2 (due to the increased aperature of a 5m facility) will push the confusion limit at ≈70μm a factor of ∼3× deeper, and a factor of ∼10× deeper at 100μm and 250μm.** For example, the measured confusion limit at 100μm from *Herschel* PACS[17] is ≈0.15 mJy, which from Figure 1, appears to correspond to a cumulative number of sources per beam (right y-axis) of ∼0.13. Assuming the same effective limit with a 5 m facility (left y-axis value of 0.13), we derive a confusion limit at 100μm of ∼11μJy. See Table 1 for our estimates at other wavelengths. The factor of ten improvement in the confusion limit at 100μm is due to the shallow slope of the faint-end of the number counts below 0.1mJy. While a steep slope would result in a less advantageous jump in the confusion limit, we know such slopes are unphysically possible as they would imply the cosmic infrared background (CIB[2]) should be several times larger than it is measured to be.

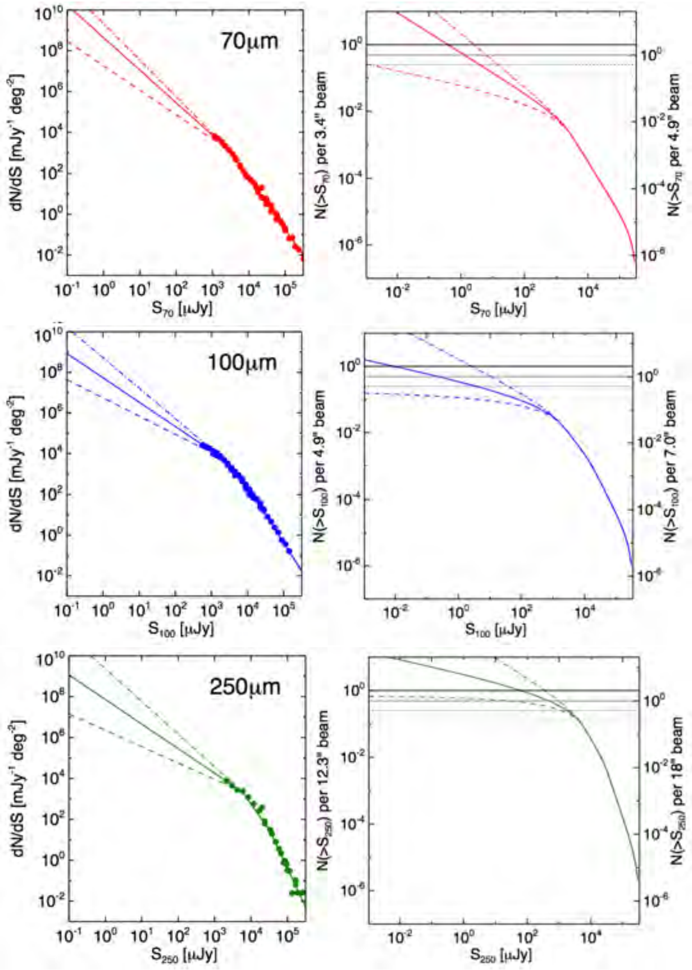


Figure 1: Differential and cumulative number counts at 70–250μm; see text for details.

So what is the scientific value of having a facility with such a low FIR confusion limit? A factor of ten in the confusion limit translates to a factor of ten improvement in the depth of FIR surveys, implying easy detection of Milky Way type galaxies in direct dust emission out to $z \sim 1.5$. The dramatic improvement in depth also implies the number of galaxies with direct detections in the FIR will increase by a factor of ∼100, extrapolating from the underlying shape of the dusty galaxy luminosity function[10]. This will allow very detailed analysis of dust emission, obscuration, and star-formation in distant galaxies on a far larger scale than has previously been possible and resolving the vast majority of individual galaxies contributing to the CIB, well below the knee of the galaxy luminosity function.

Wavelength	*Herschel* conf. lim.	5m conf. lim.	Factor of Improvement
70μm	35 μJy	11 μJy	3.2
100μm	150 μJy	11 μJy	14
250μm	460 μJy	68 μJy	7

Table 1. Estimated confusion limit for a 5m FIR facility in comparison to *Herschel*.

References: [1] Puget et al. 1996, A&A 308, 5 [2] Fixsen et al. 1998, ApJ 508, 123 [3] Neugebauer et al. ApJL 278, 1 [4] Lemke et al. 1996, A&A 315, 64 [5] Rieke et al. 2004, ApJS 154, 25 [6] Murakami et al. 2007, PASJ 59, 369 [7] Poglitsch et al. 2010, A&A 518, 2 [8] Griffin et al. 2010 A&A 518, 3 [9] Condon 1974, ApJ 188, 279 [10] Casey, Narayanan & Cooray 2014, Phys. Rep. 541, 45 [11] Dole et al. 2004, ApJS 154, 87 [12] Béthermin et al. 2010, A&A 516, 43 [13] Berta et al. 2011, A&A 532, 49 [14] Héraudeau et al. 2004, MNRAS 354, 924 [15] Rodighiero et al. 2004, A&A 419, 55 [16] Kawara et al. 2004, A&A 413, 843 [17] Magnelli et al. 2013, arXiv/1311.2956 [18] Patachon et al. 2009, ApJ 707, 1750 [19] Béthermin et al. 2010, A&A 512, 78 [20] Oliver et al. 2010, MNRAS 405, 2279 [21] Clements et al. 2010, MNRAS 403, 274 [22] Béthermin et al. 2012, ApJL, 757, 23

Far-Infrared Spectral Line Studies of the Epoch of Reionization

Asantha Cooray (UC Irvine; accooray@uci.edu), James Aguirre, Phil Appleton, Matt Bradford, Caitlin Casey, Phil Mauskopf, Bade Uzgil

Existing cosmological observations show that the reionization history of the universe at $z > 6$ is both complex and inhomogeneous. All-sky CMB polarization measurements provide the integrated optical depth to reionization. A detailed measurement of the reionization history may come over the next decade with 21-cm HI radio interferometers, provided that they are able to remove the foregrounds down to a sub-hundredth percent level. Deep sky surveys, especially those that employ gravitational lensing as a tool, are now efficient at finding Lyman drop-out galaxies at $z > 7$, though with a large systematic uncertainty on the redshift due to degeneracies between Lyman drop-out and dusty galaxy SED templates. During the next decade the study of reionization will likely move from studying galaxies during reionization from $z = 6$ to 9 to understanding primeval stars and galaxies at $z > 10$.

In the JWST era current studies that focus on the rest-frame UV and optical lines to study the ISM and gas-phase metallicities of galaxies at $z \sim 1$ to 2 will quickly extend to z of 6. In the post-JWST era a far-infrared space telescope with a factor of 10 sensitivity improvement over SPICA will enable studies on the gas properties, AGN activity and star-formation within galaxies at $z = 6$ to 15, in addition to a large list of sciences at $z < 6$. This redshift range is especially important for our understanding of the cosmic origins, formation of first stars, galaxies and blackholes, and the onset of large-scale structure we see today. The community is already struggling with many scientific issues during this epoch. For example, an outstanding problem involves the growth of supermassive blackholes and the presence of billion to ten billion solar masses backholes at $z > 6$ at an age of 600-800 Myr after the Big Bang. One possibility to grow such high masses is seed blackholes associated with massive PopIII stars. Could we directly observe the formation of such massive stars at $z \sim 12$ to 15? And could we study the blackhole activity in galaxies at $z \sim 7$ to 10 as these blackholes grow in mass rapidly to values measured at $z \sim 6$?

To aid study of reionization 20 to 600 μm spectroscopic observations can: (a) disentangle the complex conditions in the ISM of $z = 6$ to 15 galaxies by measuring the gas densities and excitation, and the prevalence of shock heating; (b) compare the conditions of the ISM in high-redshift galaxies with local galaxies to address whether faint dwarf galaxies found at low-redshifts are analogues of galaxies during reionization; (c) use spectral line diagnostics to study AGN or star-formation regulated actively within first galaxies, including the formation of first massive blackholes; and (d) detect, measure, and map out molecular hydrogen rotational line emission from primordial cooling halos that are the formation sites of first stars and galaxies at $z > 10$.

The role of far-infrared spectral capabilities will allow diagnostic studies and ways to establish the role of feedback, radiation, and AGNs, among many others, in regulating star-formation in reionization era galaxies. For example, [OIV]26 and Ne[V]14.3 are high-ionization lines that are enhanced in AGN environments and far-IR diagnostics such as [OIV]26/[SIII]33 or [NeV]14.3/[NeIII]15.6 ratios provide a direct measure of the AGN fraction to galaxy luminosity, even when there is signicant dust extinction. Such diagnostics then allow a way to distinguish galaxies at $z > 8$ that harbor AGNs and are likely to grow

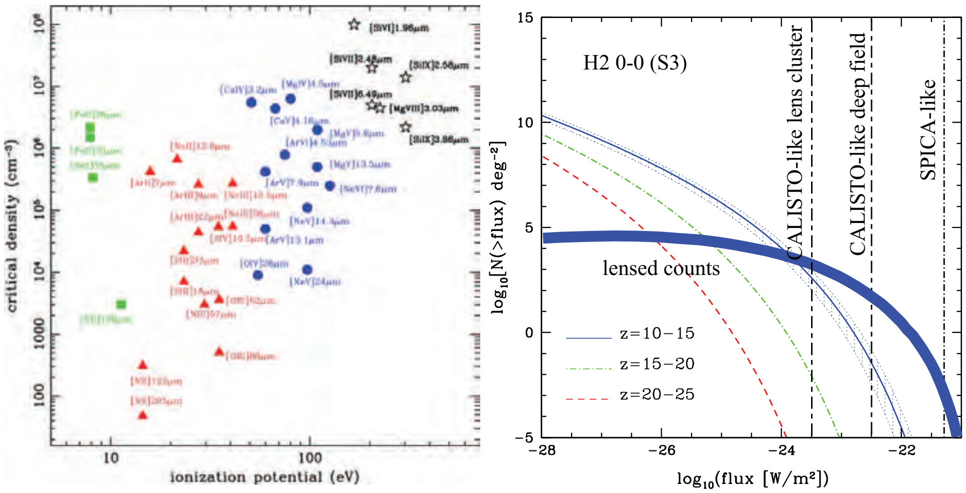


Figure 1: *Left panel:* Density-ionization diagram (Spinoglio et al. 2009) for far-IR spectra lines. Color coding shows lines separated to different conditions and radiation fields, such as stellar/HII regions or AGNs. *Right panel:* H_2 0-0 S(3) cumulative number counts as a function of the flux density (Gong et al. 2012). In addition to intrinsic counts, we also show the gravitationally lensed counts at $z > 10$ by foreground galaxies. While SPICA or SPICA-like mission will not have the sensitivity to detect molecular hydrogen in mini-halos at the onset and during reionization, a far-infrared mission with at least a factor of 10 sensitivity improvement over SPICA, such as CALISTO, will be necessary to detect many of the important molecular hydrogen lines in the rest-frame mid-infrared wavelengths. This will require a deep 1 $\deg^2$ survey over 2000 hrs. Another factor if ten depth can be achieved, on average, lensing cluster survey, similar to Hubble Frontiers Fields.

to optically luminous quasars detected with wide sky surveys such as SDSS. The mid-IR to far-IR spectral region provides both the depth and the range to initiate a wide array of studies that are still limited to lack of developments in the observational capabilities.

Moving to the highest redshifts molecular hydrogen is now understood to be the main coolant of primordial gas leading to the formation of very first stars and galaxies. It is also the most abundant molecule in the universe. There is no other signal from primordial gas cooling at the earliest epochs in either the low-frequency 21-cm background or any other cosmological probe that the community has considered. **Molecular hydrogen cooling in primordial dark matter halos will then likely the only tracer to study the transition from dark ages at $z > 20$, when no luminous sources exist, to reionization at $z < 10$.** At a metallicity $Z \sim 10^{-3.5}$ $Z_\odot$ gas cooling will transit from H_2 to fine-structure lines. At $z < 8$, when primordial molecular hydrogen is easily destroyed by UV radiation, the prevalence of shocks in the ISM may provide ways to form a second and later generations of molecular hydrogen. The rotational lines of molecular hydrogen span across a decade of wavelength from 2 to 20 μm. JWST will study molecular hydrogen out to z of 1 and SPICA may be able to study them to $z \sim$3 to 4, but at $z > 6$ SPICA does not have the required sensitivity (Fig 1 right panel).

Even if not individually detected, a far-IR survey telescope will use intensity fluctuations, similar to power spectra in CMB and Cosmic Infrared Background but in 3D due to spectral line redshift mapping, to study the spatial distribution of H_2. This intensity mapping technique also relies on a cross-correlation with a second line of H_2 from the same redshift interval to minimize foreground line contamination. The requirements for $z \sim 6$ far-IR fine-structure and $z > 10$ H_2 mapping of primeval cooling halos are 20 to 600 μm spectral coverage and a noise level below 10^{-22} W/m^2 in a deep 1000 to 2000 hour integration over a sq. degree area. CALISTO is one step in this direction.

A Joint Exoplanet & UVOIR Surveyor

Prof. Julianne J. Dalcanton

Department of Astronomy, University of Washington

In preparation for planning for the 2020 Decadal Survey, Paul Hertz asked the Program Analysis Groups to solicit input on 4 distinct missions, some of which may be studied in more detail in advance of the Decadal. This white paper would like to endorse that a *combination* of the UVOIR Surveyor and the Habitable-Exoplanet Imaging Mission be evaluated as well.

In the current framework, it is inevitable that a UVOIR Surveyor and a Habitable-Exoplanet Imaging Mission will each produce concepts that are highly optimized for their top-line science goals. There may be some additional consideration given to the needs of other communities (such as the addition of the wide field imager on TPF-C, or the coronagraph on WFIRST-AFTA), but any additional instrumentation to support a larger science community is most likely to be an "add-on" that fails to deliver on the full vision of the broader community, and that necessarily accepts compromises in the need to optimize for the primary science goal.

If one steps back, however, it is clear that many of the fundamental design considerations for both a UVOIR Surveyor and a Habitable-Exoplanet Imaging Mission are *shared* by both likely mission concepts. As such, it makes sense to consider not just specialized missions that serve each goal separately, but a joint mission that aims to optimize both.

- *Common Wavelength Coverage:* The Habitable Exoplanet Imaging Mission is likely to focus initially on the optical, where the shorter wavelength allows one to probe closer to the host star for a given inner working angle (IWA) of a coronagraph or starshade starlight suppression system. Exoplanets that are slightly more distant from their host star can benefit from near-infrared spectroscopy, which contains a number of useful lines for constraining the properties of planetary atmospheres. Thus, the wavelength coverage needed for any Habitable-Exoplanet Imaging mission is likely to be encompassed by the coverage needed for the UVOIR Surveyor.
- *A Shared Need for Large Aperture:* Detecting and characterizing significant numbers of planets in the habitable zone absolutely requires large apertures. First, the IWA scales like the inverse of the telescope diameter, such that larger telescopes can detect planets closer to their host star, increasing the chances of finding rocky habitable zone planets around solar-type stars. Second, earth-like planets are incredibly faint, so even in cases where good contrast can be achieved in the habitable zone, an enormous collecting area is needed to ensure enough photons are collected to generate a spectrum whose signal to noise sufficient to characterize the atmosphere. Likewise, for a general purpose next-generation UVOIR mission, one expects transformative science gains when capabilities increase by an order of magnitude. Compared to Hubble, a factor of 10 times increase in the collecting area and in the number of resolution elements per square arcsecond would be achieved by going to a $>$8m class facility. Thus, the most scientifically compelling UVOIR mission is likely to be of comparable diameter to that required by a likely exoplanet mission.

- *Strong Parallel Science Capabilities:* Exoplanet observations are likely to involve very long integrations. If the Habitable-Exoplanet Imaging mission is also outfitted with general purpose astrophysical instrumentation, these long integrations become a ripe opportunity for very deep parallel observations that support a rich array of other science programs (galaxy deep fields, multi-slit UV spectroscopy, grism surveys, etc). The addition of this parallel science capability not only dramatically increases the scientific efficiency, it also greatly reduces scientific risk to the Habitable-Exoplanet mission by guaranteeing scientific results even when an individual planetary system fails to yield habitable exoplanets. In addition, the broad astronomical research carried out by Hubble has proven particularly compelling to the general public; while detection of a true Earth-analogue will be a major front-page result, general astrophysics provides a steady diet of varied, compelling science results that keep the public engaged with NASA during the long exoplanet search campaign.

Because of their similar aperture requirements, comparable wavelength coverage, and synergistic observing possibilities, we argue that in some implementations it is possible to consider the Habitable-Exoplanet Imaging Mission and the UVOIR Surveyor as a single flagship mission, rather than two separate entities.

We percieve a number of risks associated with only considering these mission concepts separately. By setting up the studies as two distinct missions, NASA may be inadvertently — and unnecessarily – framing the upcoming 2020 Decadal survey as a competition between the exoplanet and general astrophysics communities. Such an approach imperils both possible missions. The history of NASA's flagship missions has repeatedly shown that the largest challenges are frequently not technical, but political. Supporting the high cost of development and operation of a flagship mission over decades requires the highest level of community engagement and advocacy, and by splitting the community too soon, we risk fragmenting the support in the earliest stages where it is most needed.

Likewise, if a joint exoplanet and general UVOIR astrophysics facility is successfully launched, the breadth of the user community will guarantee that the mission remains highly relevant across essentially all fields of astrophysics, which will keep the mission in the public and the scientific eye. This on-going relevance increases the chances that the mission will be long lived, and possibly even serviced with higher-performance second-generation instruments.

Finally, the early pre-2020 design studies proposed by NASA will be useful and necessary investments for evaluating mission cost and for developing plans for critical technology development. Failure to fund evaluation of architectures that can *simultaneously* serve both exoplanet and general astrophysics science goals instantly puts a merged concept at a major disadvantage, effectively guaranteeing that its costing will be more uncertain and more expensive, due to lack of early investment. This will effectively cut off options for pursing a merged mission prematurely.

Based on the above considerations, we strongly endorse study of a merged mission concept that simultaneously addresses the scientific goals of the exoplanet and the UVOIR communities. The much larger community support and greater potential for scientific impact greatly increases the chances that the mission will actually be built.

The earliest epoch of star-formation in the very young universe

Dennis Ebbets, dcebbets@gmail.com
April 3, 2015

Motivation: One of the most intriguing accomplishments in astrophysics during my lifetime has been the elucidation of the timeline of the origin and evolution of our universe. A particularly interesting and surprising discovery (to me) has been how quickly structures such as supermassive black holes, early galaxies and the first generations of stars got started. We see indications of Gamma Ray Bursts, quasars and proto-galaxies near redshift 7-8, corresponding to a time when the universe was barely 10% of its current age. Somewhere in this distant past, perhaps 12 billion years ago, a first epoch of star formation must have produced individual objects composed of primordial Hydrogen and Helium, whose supernova explosions started the enrichment of the otherwise pristine universe with the products of nuclear reactions in their cores and detonations. Although this scenario has been modeled and simulated with increasing sophistication, observation of these stars remains beyond the capabilities of current instruments. Studying the stellar astrophysics of this population and clarifying this period in the timeline of cosmic origins will be a worthy goal for a future large UV/Optical/IR Surveyor.

Relationship to other large missions: In the two decades before this observatory can be launched other facilities will make progress towards similar goals. JWST includes "first light" and the assembly of galaxies as important scientific themes. WFIRST-AFTA will conduct deep, high resolution surveys that will discover very young galaxies magnified by gravitational lensing. LSST will pursue sensitive time-domain science that may provide hints about SNe rates in high redshift galaxies. TMT and GMT may obtain spectra of distant star-forming regions in young galaxies. Radio experiments such as SKA and DARE may study conditions during the Dark Ages that led to the first luminous objects and reionization of the mostly neutral universe. The design and research program of the UV/Optical/IR Surveyor will benefit from these and other advances.

Some specific science objectives:

1. Show which candidate Pop III objects are stellar with core nuclear burning, not black hole accretion disks
2. Assess whether clusters of large number of objects formed together, or whether small numbers of more massive objects were favored
3. Measure their Spectral Energy Distributions over a wide wavelength range
4. Detect spectral features of H and He showing profiles attributed to stellar winds
5. Determine the highest redshifts at which stellar objects are detectable, establishing the earliest epoch of star formation
6. Measure their colors and luminosities, construct and interpret Color-Magnitude Diagrams, Luminosity Functions and/or Initial Mass Functions if statistics allow
7. Measure the sizes and environments of star-forming regions
8. Search for indications of gas or dust, such as H II regions
9. Detect the early signatures of non-zero metal content in nebular emission lines, revealing the products of p-p burning and later CNO processes, and those of explosive nucleosynthesis
10. Detect and characterize SNe events in the population of first-generation stellar objects
11. Identify the end of the epoch of first generation of stars in redshift and time.

Instrument capabilities needed:

- High spatial resolution imaging – resolve structures comparable to Carina or 30 Doradus at z=10
- Tunable filters – image in selectable rest-frame spectral bands at arbitrary redshifts
- Energy-sensitive detectors – enhance wavelength selection and rejection of out of band light
- IFS spectrograph to determine redshifts, measure SEDs and detect emission lines of H II regions

- Spectrograph capable of measuring interstellar, circum-galactic and inter-galactic absorption features at all redshifts along the line of sight

Characteristics of the telescope and observatory:

- It will be similar to HST in many respects, but may reach 5 magnitudes or more deeper
- To achieve the highest possible angular resolution the telescope will have a large diameter, 10m or more, and will be diffraction-limited in optical or shorter wavelengths
- To provide high sensitivity for faint objects it will need a large collecting area, efficient reflective coatings and instruments. V=30 may be a representative point source magnitude. $50m^2$ might be a starting point for size, as it was for the Modern Universe Space Telescope (MUST) Vision Mission concept study.
- The observatory will operate in "point and stare" mode, and will have the stability to point to a fraction of a spatial resolution element for the duration of longest exposures.
- The observatory will respond to detection of a SNe event by other facilities as a Target of Opportunity.

Technology development: If we make the reasonable assumption that the desired resolution and sensitivity will require an aperture greater than the largest fairings, then a monolithic primary seems unlikely, and technologies for a large segmented mirror will be needed. Many have been under study already. Progress on telescope and instrument technologies will need to be reported to the 2020 Decadal Survey. For example:

- It should be designed to fill the volume and mass capability of largest launch vehicle and fairing available at the time. It should not be limited by fairing diameter. This will require approaches for efficient and safe packaging, as suggested in the MUST study report.
- Technologies for robotic deployment or assembly in space.
- Robotic servicing of science instruments and observatory systems.
- IFU for IFS at all wavelengths, including UV. Does not need to be same technology for all wavelengths.
- Energy resolving detectors.
- Tunable filters with selectable central wavelengths and passbands.

Is it a large mission? In terms of physical size, versatility of its payload, operational capabilities, development cost and schedule required, yes, this will be a large mission.

- A primary goal is to provide the largest collecting area and angular resolution possible.
- Sun-Earth L2 is probably the right operational orbit.
- It will have access to the entire celestial sphere during its annual orbit.
- It will be required to remain on target for days to weeks at a time.
- It will have a lifetime of many years – long enough to observe a few SNe of Pop III objects.
- It is a general purpose observatory, available to a large community with a wide range of research interests.
- The observatory will support many science instruments, and will allow replacement and refurbishments.
- There will be a robust ground system for operations and user support, including superb communication of findings to the public.

Summary: The UV/Optical/IR Surveyor will be a worthy successor to HST, JWST and AFTA in scientific accomplishments, a decade or more of service to a large community of extremely capable researchers, and recognition by an informed and receptive public. Every mission pushes back farther in time and space. The investigations of the earliest epoch of star formation and production of heavy elements described here are unlikely to be accomplished by other ground or space-based observatories in the near future.

Characterizing the Habitable Zones of Exoplanetary Systems with a Large Ultraviolet/Visible/Near-IR Space Observatory

Kevin France[1*], Evgenya Shkolnik[2], Jeffrey Linsky[1], Aki Roberge[3], Thomas Ayres[1], Travis Barman[4], Alexander Brown[1], James Davenport[5], Jean-Michel Desert[1], Shawn Domagal-Goldman[3], Brian Fleming[1], Juan Fontenla[6], Luca Fossati[7], Cynthia Froning[8], Gregg Hallinan[9], Suzanne Hawley[5], Renyu Hu[10], Lisa Kaltenegger[11], James Kasting[12], Adam Kowlaski[13], Parke Loyd[1], Pablo Mauas[14], Yamila Miguel[15], Rachel Osten[16], Seth Redfield[17], Sarah Rugheimer[18], Christian Schneider[19], Antigona Segura[20], John Stocke[1], Feng Tian[21], Jason Tumlinson[16], Mariela Vieytes[14], Lucianne Walkowicz[22], Brian Wood[23], and Allison Youngblood[1]

[1]University of Colorado, [2]Lowell Observatory, [3]NASA/GSFC, [4]U. Arizona, [5]U. Washington, [6]NWRA, [7]U. Bonn, [8]U. Texas, [9]Caltech, [10]JPL, [11]Cornell, [12]Penn State, [13]U. Maryland, [14]IAFE , [15]Observatoire de la Côte d'Azur, [16]STScI, [17]Wesleyan, [18]Harvard, [19]ESA/ESTEC, [20]UNAM, [21]Tsinghua U., [22]Adler Planetarium, [23]NRL

Understanding the surface and atmospheric conditions of Earth-size ($R_P \approx 1 - 1.5\ R_\oplus$), rocky planets in the habitable zones (HZs) of low-mass stars is currently one of the greatest astronomical endeavors. The Astro2010 Decadal Survey ranks the **"Identification and characterization of nearby habitable exoplanets"** as the premier Discovery Goal for astrophysics at present, with **"can we identify the telltale signs of life on an exoplanet?"** as a specific focus question. The nearest known Super-Earth mass planets ($2 - 10\ M_\oplus$) in the HZ orbit late-type stars (M and K dwarfs). In addition, all of the HZ planets found by *TESS* will be around M dwarfs, making these systems prime targets for spectroscopic biomarker searches with *JWST* and future direct spectral imaging missions (Deming et al. 2009; Belu et al. 2011).

The planetary effective surface temperature alone is insufficient to accurately interpret biosignature gases when they are observed in the coming decades. The UV stellar spectrum drives and regulates the upper atmospheric heating and chemistry on Earth-like planets, is critical to the definition and interpretation of biosignature gases (e.g., Seager et al. 2013), and may even produce false-positives in our search for biologic activity (Hu et al. 2012; Tian et al. 2014; Domagal-Goldman et al. 2014). Therefore, our quest to observe and characterize biological signatures on rocky planets *must* consider the star-planet system as a whole, including the interaction between the stellar irradiance and the exoplanetary atmosphere.

Spectral observations of O_2, O_3, CH_4, and CO_2, are expected to be important signatures of biological activity on planets with Earth-like atmospheres (Des Marais et al. 2002; Kaltenegger et al. 2007; Seager et al. 2009). The chemistry of these molecules in the atmosphere of an Earth-like planet depends sensitively on the strength and shape of the host star's UV spectrum. H_2O, CH_4 , and CO_2 are sensitive to far-UV radiation (FUV; 100 – 175 nm), in particular the bright HI Lyα line, while the atmospheric oxygen chemistry is driven by a combination of FUV and near-UV (NUV; 175 – 320 nm) radiation (Fig 1). Furthermore, the FUV and NUV bandpasses themselves may be promising spectral regimes for biomarker detection (Bétrémieux & Kaltenegger 2013). High levels of extreme-UV (EUV; 10 – 91 nm) irradiation can drive hydrodynamic mass loss on all types of exoplanets (e.g., Koskinen et al. 2013; Lammer et al. 2014). Ionization by EUV photons and

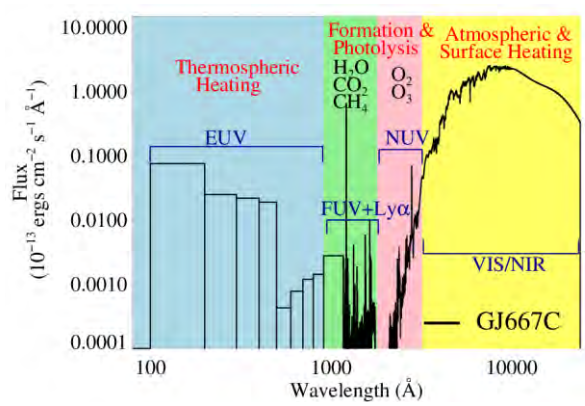


***Figure 1**: HST spectrum of GJ 667C, illustrating the influence of each spectral bandpass on the atmosphere of an Earth-like planet orbiting this star (France et al. 2013, Linsky et al. 2014). GJ 667C hosts a super-Earth mass planet located in the HZ.*

*kevin.france@colorado.edu; 1-303-492-1429

the subsequent loss of atmospheric ions to stellar wind pick-up can also drive wide-scale atmospheric mass loss on geologic time scales. As the opacity of the ISM precludes direct observations of the EUV irradiance, FUV observations provide the best constraints on the EUV emission from cool stars (Linsky et al., 2014; Shkolnik & Barman 2014).

The temporal variability of these sources must also be considered as even weakly-active, "old" (several Gyr) M dwarfs show extreme flare events in their UV light curves (factors of greater than 10 flux increases on time scales of minutes, see Fig. 2; France et al. 2013; Loyd & France 2014). Impulsive UV events are also signposts for energetic flares, those that are associated with large ejections of charged particles. Energetic particle deposition into the atmosphere of an Earth-like planet during a large M dwarf flare can lead to significant atmospheric O_3 depletions (> 90% for large flares; Segura et al. 2010). This alters the atmospheric chemistry and increases the penetration depth of UV photons that could potentially sterilize (or catalyze) surface life. Given that particle fluxes cannot typically be directly measured for stars other than the Sun, UV observations offer the best estimates of these important particle environments.

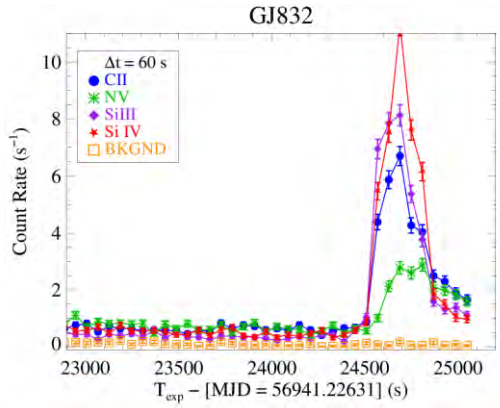


Figure 2*: FUV flare on the "optically inactive" M dwarf GJ 832 (d = 4.9 pc), illustrating a flare event in FUV emission lines on sub-minute timescales (HST-COS data, binned to 60 s intervals).*

NASA's next large ultraviolet/optical/infrared flagship mission, a LUVOIR Surveyor, could carry out both the direct detection of atmospheric tracers on these worlds and the essential characterization of the star-planet system. The transformative science enabled by a LUVOIR Surveyor to the field of astronomy as a whole, including exoplanet (ExoPAG) and cosmic origins (COPAG) themes, is made clear in NASA's 2013 Astrophysics Roadmap (*Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades*): a LUVOIR Surveyor (or ATLAST/HDST-like mission; Tumlinson et al. 2015) directly addresses the largest number of core NASA science priorities in a single mission in the next 30 years, working toward six "primary goals", ***twice as many core science goals as any other intermediate-term mission concept*** (Section 6.4 in 2013 Roadmap).

There are a set of baseline requirements for the characterization of the energetic radiation environments around low-mass exoplanet host stars. Spectral coverage to wavelengths as short as 102 nm is crucial to characterizing the star in important activity tracers (e.g., O VI and Lyα), as well as peak absorption cross-sections for relevant molecular species in planetary atmospheres (e.g., O_2 and H_2). We would like to characterize typical mid-M dwarf exoplanet host stars out to 30 pc with sufficient signal-to-noise to carry out time-resolved, $R \approx 3000$ spectroscopy of UV emission lines (e.g., N V, Si IV, C IV; $F_\lambda \sim 1 \times 10^{-16}$ erg cm^{-2} s^{-1}) on the scale of minutes (S/N ~ 10 per 60 s). These sensitivities can be achieved with a 10-meter class mirror, optical coatings with broadband UV reflectivity ≥ 90%, and photon-counting detectors with UV DQE ≥ 75%. These technology goals can be achieved with a reasonable investment in laboratory development efforts and hardware demonstration flights (via suborbital and small satellite missions; e.g., France et al. 2012) in the next 5 – 10 years, enabling the start of a LUVOIR Surveyor mission in the 2020s.

References: Belu at al. 2011A&A...525A..83B; Bétrémieux & Kaltenegger 2013ApJ...772L..31B; Blandford et al. 2010, Nat Acad. Press; Deming et al. 2009PASP..121..952D; des Marais et al. 2002AsBio...2..153D; Domagal-Goldman et al. 2014ApJ...792...90D; France et al. 2013ApJ...763..149F; France et al. 2012SPIE.8443E..05F; Hu et al. 2012ApJ...761..166H; Kaltenegger et al. 2007ApJ...658..598K; Koskinen et al. 2013Icar..226.1678K; Lammer et al. 2014MNRAS.439.3225L; Linsky et al. 2014ApJ...780...61L; Loyd & France 2014ApJS..211....9L; Seager et al. 2013ApJ...777...95S; Seager et al. 2009and..book..123S; Segura et al. 2010AsBio..10..751S; Shkolnik & Barman 2014AJ....148...64S; Tian et al. 2014E&PSL.385...22T; Tumlinson et al. 2015AAS...22533819T

The bulk composition of exo-planets

Boris Gänsicke (University of Warwick), John Debes (STScI), Patrick Dufour (University of Montreal), Jay Farihi (UCL), Michael Jura (UCLA), Mukremin Kilic (University of Oklahoma), Carl Melis (UCSD), Dimitri Veras (University of Warwick), Siyi Xu (ESO), Ben Zuckerman (UCLA)

Motivation

Priorities in exo-planet research are rapidly moving from finding planets to characterizing their physical properties. Of key importance is their chemical composition, which feeds back into our understanding of planet formation. Mass and radius measurements of transiting planets yield bulk densities, from which interior structures and compositions can be deduced (Valencia et al. 2010). However, those results are model-dependent and subject to degeneracies (Rogers & Seager 2010; Dorn et al. 2015). Transmission spectroscopy can provide insight into the atmospheric compositions (Sing et al. 2013; Deming et al. 2013), though cloud decks detected in a number of super earths systematically limit the use of this method (Kreidberg et al. 2014). *For the foreseeable future, far-ultraviolet spectroscopy of white dwarfs accreting planetary debris remains the only way to directly and accurately measure the bulk abundances of exo-planetary bodies. The exploitation of this method is limited by the sensitivity of HST, and significant progress will require a large-aperture space telescope with a high-throughput ultraviolet spectrograph.*

Evolved planetary systems

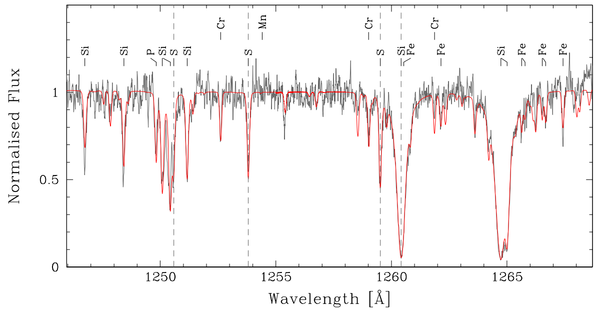
Practically all known planet host stars, including the Sun, will evolve into white dwarfs, and many of their planets will survive (Veras et al. 2013; Villaver et al. 2014). Observational evidence for such evolved planetary systems includes the detection of trace metals in the white dwarf photospheres (Koester et al. 1997), and infrared and optical emission from circumstellar debris disks (Zuckerman & Becklin 1987; Gänsicke et al. 2006; Farihi et al. 2009). The generally accepted model explaining these observation is the tidal disruption of asteroids, minor planets, or planets (Jura 2003; Debes et al. 2012; Veras et al. 2014) perturbed onto star-crossing orbits by dynamical interactions with planets (Debes & Sigurdsson 2002; Frewen & Hansen 2014; Veras & Gänsicke 2015). Spectroscopic surveys now unambiguously demonstrate that 25-50% of white dwarfs host evolved planetary systems (Zuckerman et al. 2003, 2010; Koester et al. 2014).

Debris-polluted white dwarfs as tracers of exo-planet bulk abundances

In a pioneering paper, Zuckerman et al. (2007) showed that measuring the photospheric abundances of debris-polluted white dwarfs provides an unrivaled window into the bulk composition of exo-planetary material for planetary bodies with masses of $10^{20} - 10^{25}$ g (Girven et al. 2012), i.e. ranging from several 10 km-sized asteroids to nearly the mass of Pluto.

The ultraviolet wavelength range is fundamental for this work, as it contains strong transitions of the rock-forming elements (Si, Fe, Mg, O), refractory litophiles (Ca, Al, Ti), and in particular of volatile elements (C, N, P, S) that trace the formation region of the planetary material relative to the snow line. We have led ten *HST*/COS programs that demonstrated the diagnostic potential of extra-solar cosmochemistry using white dwarfs, corroborating the rocky, volatile-depleted nature of the planetesimals (Jura et al. 2012; Xu et al. 2013), and detecting a variety in bulk compositions similar to, if not exceeding, that seen among solar-system bodies (Gänsicke et al. 2012, see Fig. 1). Noticeably, we have discovered water-rich planetesimals (Farihi et al. 2013), which provide the potential for delivering water to planets in the habitable zone.

The measured planetary debris abundances provide important input into our understanding of planet formation. Of particular importance for the properties of planetary systems are the C/O and Mg/Si ratios. C/O ratios > 0.8 would result in a radically different setup from the solar system, with O-chemistry replaced by C-chemistry, which is discussed abundantly in the literature (e.g. Moriarty et al. 2014). The Mg/Si ratio determines the exact composition of silicates, which in turn has implications for planetary processes such as plate tectonics. Furthermore, the relative abundances of Fe and siderophiles (Cr, Mn, S, Ni), and of refractory litophiles (Al, Ca, Ti) provides insight into the core and crust formation, respectively (Jura &



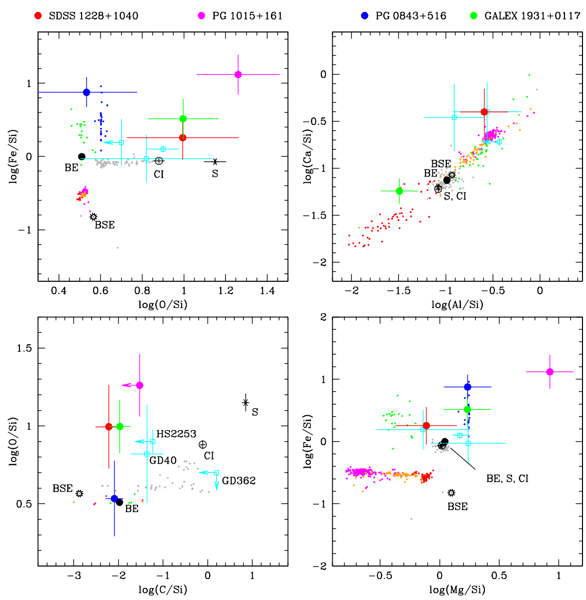


Figure 1. Planetary debris is detected in far-ultraviolet spectroscopy of white dwarfs (top), providing bulk-abundances for exo-planetary bodies with masses of $\simeq 10^{20} - 10^{25}$ g. About 15 systems studied so far are all "rocky", but show a large variety in their detailed compositions (right: large dots with error bars are extra-solar planetesimals, small dots are solar system meteorites).

Young 2014; Melis et al. 2011; Dufour et al. 2012). In contrast to indirect measurements, such as abundance studies of planet host stars (e.g. Delgado Mena et al. 2010), far-ultraviolet spectroscopy of debris-polluted white dwarfs provides a *direct measure* of those ratios. The results from our published studies of have already informed recent models of planet formation (Carter-Bond et al. 2012).

However, global insight into the chemistry of planetary systems will only be possible from the detailed photospheric abundance studies of a substantial number of white dwarfs. The current roster of planetary debris abundance studies with at least five detected elements stands at $\simeq$ 15 (Jura & Young 2014). With *HST*, we may double, maybe triple this number over the next couple of years, but beyond that, the aperture of Hubble is too small to make significant progress.

Road-map for the next two decades, and the need for a large UV mission

Over the next four years, *Gaia* will identify $\simeq$ 200 000 white dwarfs brighter than 20th magnitude. This sample will be volume-limited out to 300pc for white dwarfs with cooling ages of up to 600Myr, i.e. sufficiently hot to have significant ultraviolet flux. Ground-based spectroscopic follow-up of this sample (DESI/WEAVE/4MOST) will identify 1000s of strongly polluted white dwarfs, but typically only provide abundances for Ca and/or Mg. In addition, cross-correlation of the *Gaia* white dwarfs with the *EUCLID* and *WFIRST* surveys will result in the detection of 100s, possibly 1000s of debris discs. The detection of circumstellar debris is a direct proxy for metal-pollution at ultraviolet wavelengths. A subset of these debris discs will be bright enough to be followed-up with *JWST*/MIRI, providing detailed mineralogy. Those systems are particularly valuable, as the dust mineralogy can be directly compared to atomic abundances obtained from far-ultraviolet spectroscopy of the debris-polluted white dwarfs.

In other words, the known sample of evolved planetary systems will explode, similar to the dramatic increase in the number of planets around main-sequence stars we witness thanks to missions like *Kepler*, *TESS*, and *PLATO*. To fully exploit the potential of evolved planetary systems for a detailed, large-scale statistical study of the bulk abundances of exo-planetary systems requires a large-aperture ultraviolet mission that can provide follow-up spectroscopy for several hundred debris-polluted white dwarfs.

Instrumental requirements

Assuming a factor 30 increase in sensitivity compared to COS ($\times 15$ for a 10 m aperture, and $\times 2$ from improved optics, and improved orbital visibility) will increase the available volume for detailed abundance studies by a factor $\simeq 150$ compared to what can be reached with *HST*, sufficient to include > 1000 potential targets for high-quality ultraviolet spectroscopic follow-up.

- Spectral resolution. A resolution of at least 20 000, better 50 000 is necessary to resolve photospheric and interstellar features, and to avoid blending of lines.
- Spectral range. The "traditional" far-ultraviolet range 1100 to 1800 Å contains most of the relevant atomic transitions. Extending coverage to 950 Å, i.e. including Lyβ and Lyγ, would be greatly improve the atmospheric parameters, $T_{\rm eff}$ and $\log g$, which, in turn, result in more accurate diffusion velocities, and finally abundances. The shorter-wavelength range also contains a number of higher-ionization lines detected in hotter, younger white dwarfs.
- Signal-to-noise ratio. The abundance measurements require a minimum S/N of 40 to model the strongest absorption lines. Detection of trace species not observed so far (e.g. N, rare earth elements) will need higher S/N, of up to 100, which is currently difficult to obtain with COS because of the limited telescope aperture, and fixed-noise patterns in the detectors.

References

Carter-Bond, J. C., O'Brien, D. P., Delgado Mena, E., et al. 2012, ApJ Lett., 747, L2
Debes, J. H. & Sigurdsson, S. 2002, ApJ, 572, 556
Debes, J. H., Walsh, K. J., & Stark, C. 2012, ApJ, 747, 148
Delgado Mena, E., Israelian, G., González Hernández, J. I., et al. 2010, ApJ, 725, 2349
Deming, D., Wilkins, A., McCullough, P., et al. 2013, ApJ, 774, 95
Dorn, C., Khan, A., Heng, K., et al. 2015, ArXiv:1502.03605
Dufour, P., Kilic, M., Fontaine, G., et al. 2012, ApJ, 749, 6
Farihi, J., Gänsicke, B. T., & Koester, D. 2013, Science, 342, 218
Farihi, J., Jura, M., & Zuckerman, B. 2009, ApJ, 694, 805
Frewen, S. F. N. & Hansen, B. M. S. 2014, MNRAS, 439, 2442
Gänsicke, B. T., Koester, D., Farihi, J., et al. 2012, MNRAS, 424, 333
Gänsicke, B. T., Marsh, T. R., Southworth, J., & Rebassa-Mansergas, A. 2006, Science, 314, 1908
Girven, J., Brinkworth, C. S., Farihi, J., et al. 2012, ApJ, 749, 154
Jura, M. 2003, ApJ Lett., 584, L91
Jura, M., Xu, S., Klein, B., Koester, D., & Zuckerman, B. 2012, ApJ, 750, 69
Jura, M. & Young, E. D. 2014, Annual Review of Earth and Planetary Sciences, 42, 45
Koester, D., Gänsicke, B. T., & Farihi, J. 2014, A&A, 566, A34
Koester, D., Provencal, J., & Shipman, H. L. 1997, A&A, 320, L57
Kreidberg, L., Bean, J. L., Désert, J.-M., et al. 2014, Nat, 505, 69
Melis, C., Farihi, J., Dufour, P., et al. 2011, ApJ, 732, 90
Moriarty, J., Madhusudhan, N., & Fischer, D. 2014, ApJ, 787, 81
Rogers, L. A. & Seager, S. 2010, ApJ, 712, 974
Sing, D. K., Lecavelier des Etangs, A., Fortney, J. J., et al. 2013, MNRAS, 436, 2956
Valencia, D., Ikoma, M., Guillot, T., & Nettelmann, N. 2010, A&A, 516, A20
Veras, D. & Gänsicke, B. T. 2015, MNRAS, 447, 1049
Veras, D., Leinhardt, Z. M., Bonsor, A., & Gänsicke, B. T. 2014, MNRAS, 445, 2244
Veras, D., Mustill, A. J., Bonsor, A., & Wyatt, M. C. 2013, MNRAS, 431, 1686
Villaver, E., Livio, M., Mustill, A. J., & Siess, L. 2014, ApJ, 794, 3
Xu, S., Jura, M., Klein, B., Koester, D., & Zuckerman, B. 2013, ApJ, 766, 132
Zuckerman, B. & Becklin, E. E. 1987, Nat, 330, 138
Zuckerman, B., Koester, D., Melis, C., Hansen, B. M., & Jura, M. 2007, ApJ, 671, 872
Zuckerman, B., Koester, D., Reid, I. N., & Hünsch, M. 2003, ApJ, 596, 477
Zuckerman, B., Melis, C., Klein, B., Koester, D., & Jura, M. 2010, ApJ, 722, 725

Flagship Missions for the Decadal Review
James Green, University of Colorado

I believe that flagship missions should be “Observatories” and need to be designed to serve the astronomical community for decades. As such, they should be capability driven – and not necessarily driven by a single science question. HST, Chandra and Spitzer are examples of this widely applicable science capability concept, and I would hope that the next flagship would be as capable and successful as those missions. While specific science questions will be used to drive the design and capability, a true flagship mission must have broad capabilities that can used for decades as new questions arise, and not so uniquely designed and optimized around a single science goal that it is less useful for broad applications.

I also believe it is foolish to try and define the science problems that will dominate astronomy in 2037 – the likely launch date for the number 1 priority of the 2020 decadal survey. Consider the state of astronomy 22 years ago – 1993 – and ask if we could have identified then what are the “key science” questions that we are concerned with today?

Astronomy has two basic tools: imaging and spectroscopy.
And despite desires to make it otherwise – technology is wavelength driven and therefore, observatories are wavelength driven.

I endorse the study of three observatories:
These should have large FOV’s, exquisite angular resolution, integral field spectroscopy and high resolution spectroscopy. These are identified within the astrophysics division call:

A) “Cold” IR (JWST band or redder – but cryo coolers, not cryogen, for maximum lifetime, with a significant (> 5 X) resolution improvement over JWST
B) UV/Optical/”warm” IR (basically HST band) with 0.01 arcsecond resolution and sensitivity to perform high resolution spectroscopy down to $V_{mag} = 29$.
C) X-ray with spectroscopy of R > 10,000, the ability to image accretion disks, and the effective area to support these goals

The community should be asked for science cases to justify the required angular/spectral resolution and sensitivity. These science cases will be the starting point for the SDT’s.

The exo-planet characterization is a focused mission, and the current techniques/technologies needed to achieve its goals will render the observatory less broadly capable and I do not believe that such a mission can meet the “breadth standard” for a flagship observatory. Therefore, I feel that it should be studied as a focused, probe class mission.

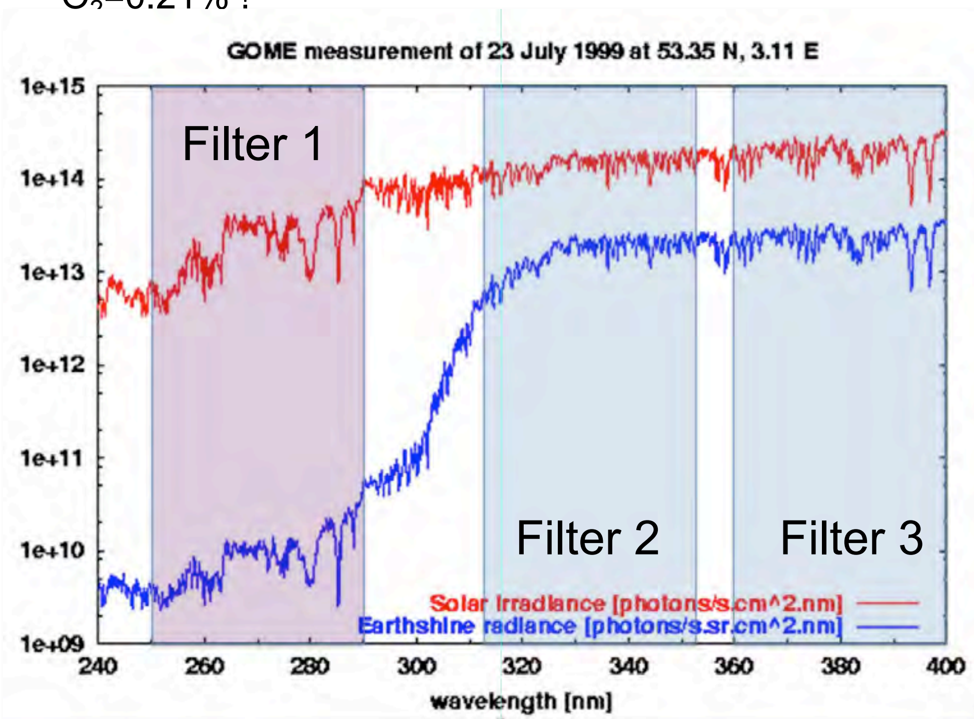
Life-Finder
S. Heap / GSFC

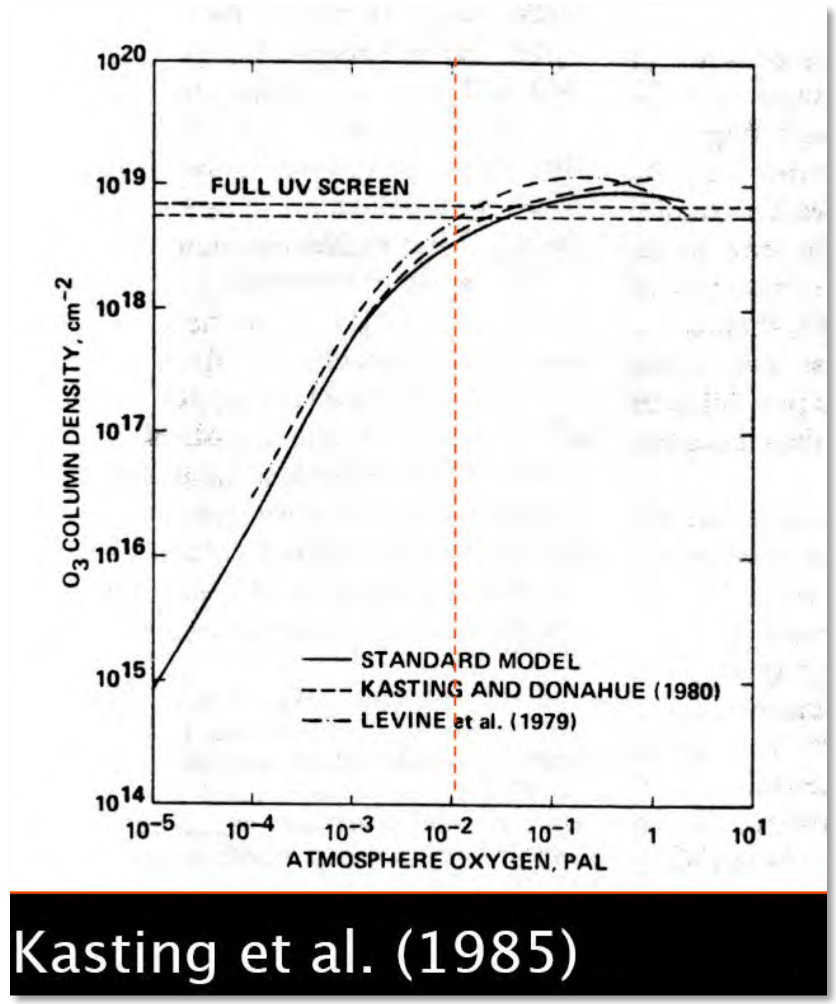
A 4-m UV/optical telescope + external occulter will

be the most powerful life-finder telescope, because

(1) it is sensivitve to low amounts of O_2

Left: Spectra of the Earth by GOME
show that O_3 absorption band is saturated
at λ<300 nm
Right: the O_3 band is expected to be saturated down to
O_2=0.21% !

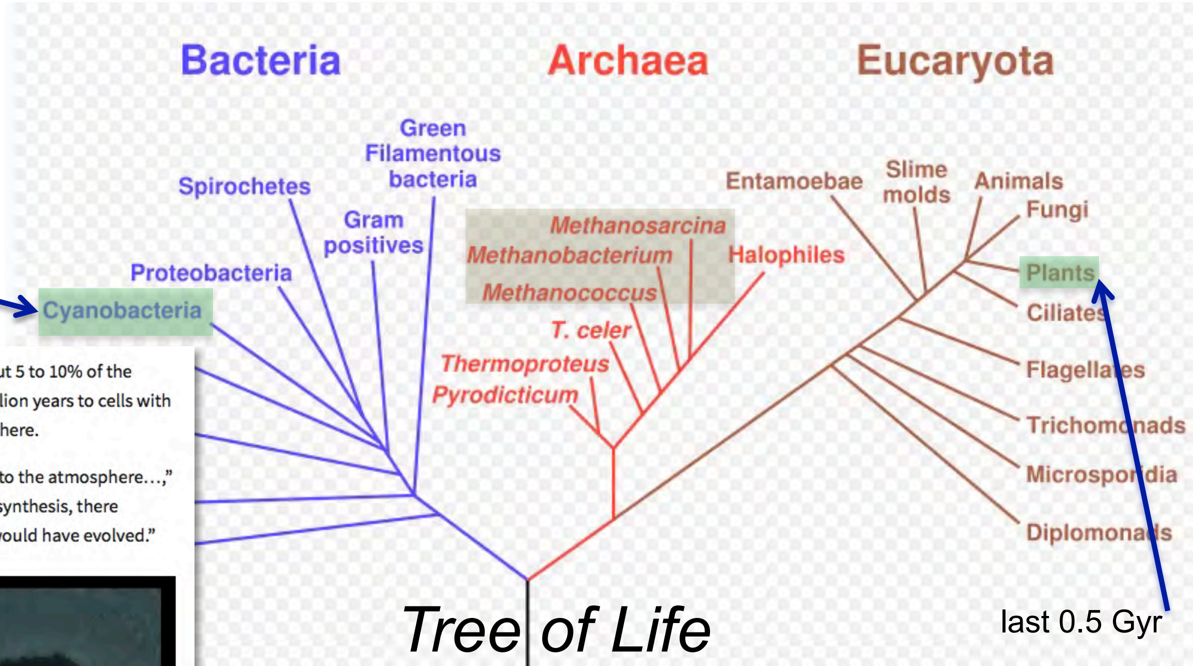




(2) Because O_3 can be detected by filter photometry

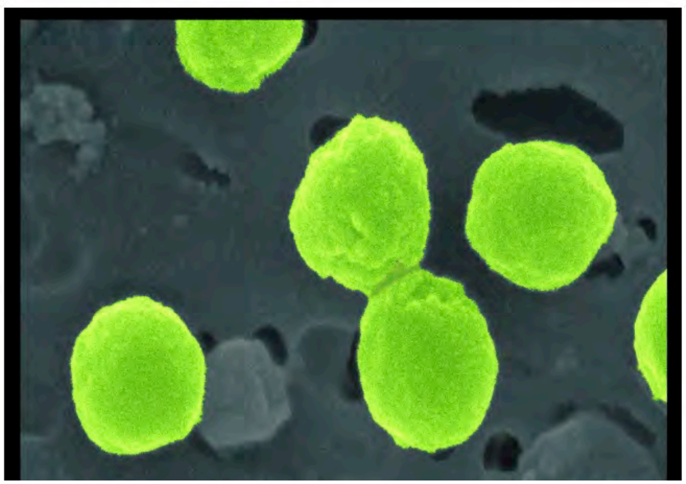
(3) Because cyanobacteria created O_2 on the early Earth (1 Gyr)

Photosynthesizing
marine organisms
last 3.5 Gyr



Chisholm estimates that Prochlorococcus is responsible for about 5 to 10% of the photosynthesis on Earth today. She traces its origins back 3.5 billion years to cells with mutations that resulted in the release of oxygen into the atmosphere.

“They split water, which is H2O, and that oxygen was released into the atmosphere…,” she said. “So if these cells hadn’t discovered, so to speak, photosynthesis, there wouldn’t be oxygen in our atmosphere, and we certainly never would have evolved.”

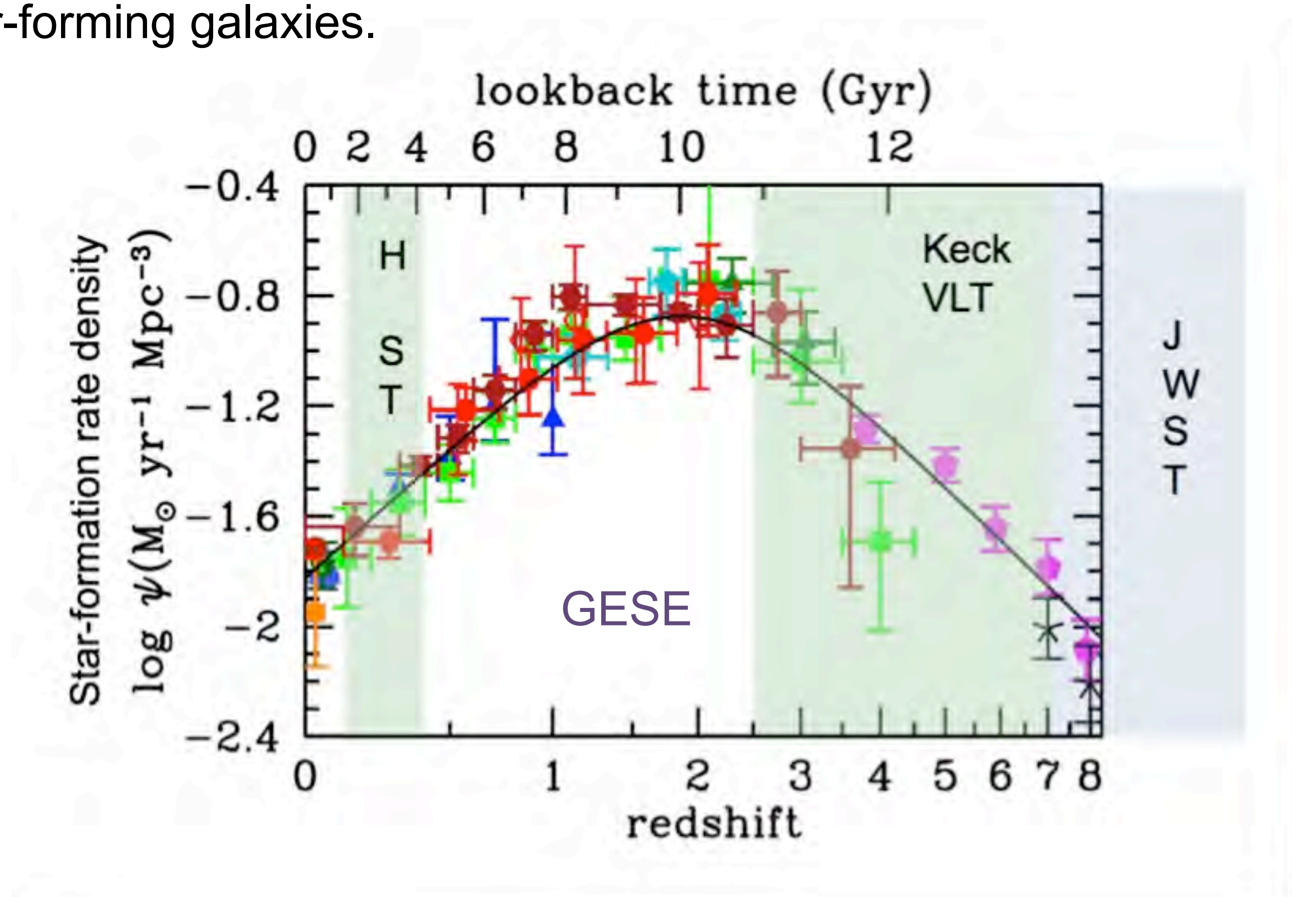


http://www.pbs.org/newshour/updates/tiny-ocean-organism-brought-earth-life/

Prochlorococcus phytoplankton, this single-celled ocean-dwelling organism, forms the “invisible pasture of the sea” that may be responsible for life as we know it on Earth. Photo by Anne Thompson, Chisholm Lab, MIT

Galaxy Evolution Spectroscopic Surveyor (GESS)
S. Heap, GSFC

GESS will survey the galaxies at redshifts, z~1-2 in the near-ultraviolet (restframe far- ultraviolet). GESS is a UV multi-object spectrograph (MOS) with instantaneously configurable slits provided by a micro-shutter array (MSA). It will survey >100,000 z~1-2 star-forming galaxies.



GESS will team up with Subaru's Prime Focus Spectrograph (PFS) to observe star-forming z~1-2 galaxies, together providing the full suite of diagnostics about the stars, gas, and dust in these galaxies.

	GESE	Subaru/PFS
Scientific Goals	Galaxy evolution	Galaxy evolution (1 of 3)
Primary targets	z~0.8-2.0 galaxies	z~0.8-2 galaxies
Wavelength coverage	0.2-0.4 μm (spec); 0.4-0.8 μm (img)	0.4-1.3 μm
Shutter/fiber FOV	2.75"x5.50"	1.0" diameter
Field of View	0.084 sq. deg.	1.1 sq. deg.
Coverage of Lyman α	z~0.7-2.2	z>2.2
Telescope	1.5 m	8.2 m
Primary mission	3 years (~25,000 hr)	100 nights
Exposure time	5 hr	~0.3-3 hr
Spectra per exposure	50-100	2000
Spectra density	600-1200 spec/deg^2	1800 spec/deg^2
Sensitivity	few x10^{-18} erg/s/cm^2/A	few x10^{-18} erg/s/cm^2/A

White Paper for the COPAG – Input for Large Astrophysics Missions

Precision Ages for Milky Way Star Clusters

Jason Kalirai[1,2] (jkalirai@stsci.edu)

[1] STScI, 3700 San Martin Drive, Baltimore, MD, 21218

[2] Center for Astrophysical Sciences, JHU, Baltimore, MD 21218, USA

Age Dating Star Clusters and Associated Uncertainties

Our knowledge of the fundamental properties of the Milky Way globular cluster system establishes a foundation for testing several aspects of the formation time and assembly of galaxies. These systems are not only among the oldest objects in the Universe, but they accompany most major star formation episodes in galaxies (e.g., Brodie & Strader 2006). Significant improvements in the ages of the Milky Way globular cluster population would immediately impact several astrophysical studies. For example,

- The *absolute* age determination of the Milky Way population represents one of the most reliable measures of when baryonic structure formation occurred in the Universe (Spergel et al. 2003). If it can be established that the oldest, metal-poor clusters indeed formed >13 Gyr ago with sub-Gyr precision, then they *must* have formed in very low mass halos and been affected by reionization (Bullock & Johnston 2005; Gnedin 2010).

- A robust slope in the globular cluster age-metallicity relation can also anchor high-resolution N-body simulations of galaxy formation, by informing the subsequent mass-merger history (Mackey & Gilmore 2004; Font et al. 2011; Beers et al. 2012). As an example, recent discoveries of outer halo GCs in M31 reveal a striking correlation between their positions and that of tidal debris streams (Mackey et al. 2010).

- The *relative* age difference between clusters associated with distinct structural components establishes the formation and assembly timescales of these parent populations (e.g., the bulge, halo, and substructure). For example, the ages of the metal-rich bulge clusters is the best method to place the formation time of the bulge within the landscape of galaxy formation models.

Modern derivations of globular cluster ages have primarily involved reproducing visible-light color-magnitude diagrams (CMDs) and the main-sequence turnoff feature with stellar evolution models. These studies have been greatly impacted by the Hubble Space Telescope, which has been used to uniquely explore dense cluster environments with high-resolution and high-precision imaging. For example, the Advanced Camera for Surveys Treasury Survey of globular clusters provides homogeneous and accurate photometry for thousands of individual stars in each of 60 systems, and is the current state-of-the-art study of both relative and absolute ages (Sarajedini et al. 2007). Recent analysis of these data, based on a uniform set of stellar evolution models with updated physics (Marin Franch et al. 2009; Dotter et al. 2010, 2011), suggests that the bulk of the Milky Way's globular clusters formed more than 12.0 Gyr ago, the oldest of which formed just a few hundred Myr after the Big Bang (Dotter et al. 2010; see also VandenBerg et al. 1996; Gratton et al. 1997; Chaboyer et al. 1998).

Despite the many advances in establishing high-precision globular cluster CMDs, the current state-of-the-art analysis of the main-sequence turnoff feature still leads to large errors in the derived absolute age of any given Milky Way cluster. For example, stellar models on the hydrogen-burning main sequence are impacted by uncertainties in nuclear reaction rates, chemical composition (e.g., [α/Fe]), the equation of state, and several second order effects including diffusion, rotation, and turbulence. Comparisons between fixed observational data sets and families of models that make different assumptions on the micro- and macrophysics of stellar structure lead to $\sim$0.5 Gyr differences in the derived age alone (Chaboyer & Krauss 2002). In addition to these uncertainties from stellar models, an additional 0.5 Gyr uncertainty results from uncertainties in the globular cluster metallicity. The *largest* uncertainty impacting this technique comes from simultaneously "fitting" the age at a given distance and reddening (σ = 1.0 to 1.5 Gyr – Dotter et al. 2011; Chaboyer 2008). For the latter, future GAIA distances to clusters will be very useful.

White Dwarf Cooling

After the hydrogen-burning main-sequence and post main-sequence evolutionary stages, the end product of 98% of all stars will be the white dwarf stage of stellar evolution. As white dwarfs, stars have no nuclear energy sources and have a very simple structure with a thin hydrogen envelope. Over time, the stars simply cool and become dimmer. On the CMD of a co-eval population, the white dwarfs will pile up on the faint-blue end and form a distinct sequence. The fainter stars are those that have been cooling longer, representing the remnants of more massive progenitors that exhausted their hydrogen supply faster.

Given their '"simple" evolution, a detection of the white dwarf cooling sequence and its limiting luminosity can enable a sensitive measurement of the age of the parent population. Over an age range of 10 – 13 Gyr, this limiting luminosity will vary by >1 magnitude in a visible-light CMD, many times larger than the luminosity or color difference of similar age models at the hydrogen-burning main sequence. The challenge is to measure these faint stars within a dense population such as a globular cluster; the faintest white dwarfs have $M_{\rm V}$ =

16.5, implying $V > 29$ in the *nearest* Milky Way globular clusters.

Over the past decade, three very large programs on the Hubble Space Telescope have successfully measured the complete white dwarf cooling sequences in the three nearest Milky Way globular clusters (Hansen et al. 2004; 2007; 2013; also Bedin et al. 2009). These studies each required 100+ orbits. For a given set of white dwarf models, sub-Gyr ages are published for each cluster. Although white dwarf models are not free of uncertainties (e.g., the onset of core-crystallization), most of the systematics are well understood and are also completely independent to the main-sequence turnoff physics.

As an example of the power of the white dwarf technique, Figure 1 illustrates the superimposed CMD of two of the globular clusters, NGC 6397 and 47 Tuc, after removing differences in distance and reddening. Whereas the locus of the stellar main-sequence is very different in the two CMDs (e.g., due to differences in metallicity), the white dwarf cooling sequences overlap almost perfectly, thereby affirming the simple nature of these stars. In this specific example, the white dwarf cooling sequence in the metal-rich cluster 47 Tuc is clearly truncated at a brighter luminosity than the metal-poor cluster NGC 6397, thereby indicating that the cluster is younger (Hansen et al. 2013).

Sub-Gyr Ages for the Milky Way Globular Cluster Population

The Hubble Space Telescope imaging projects in M4, NGC 6397, and 47 Tuc provide a strong "proof of concept" for measuring and characterizing the white dwarf populations of dense globular clusters. However, it is difficult to use these three measurements alone to address the global goals introduced above, and further Hubble observations of more clusters are unfeasible given their large foreground extinctions and/or larger distances.

A transformative breakthrough in establishing sub-Gyr ages for a family of Milky Way globular clusters, each with their own metallicity, orbit, galaxy component association, and dynamical state, will require a large aperture and high-resolution telescope, with excellent visible-light throughput. The LUVOIR telescope from the NASA Astrophysics 30-year Roadmap[1] is perfectly suited for this science goal. For example, for a $\sim$10-m space telescope, the 10σ depth in a 10-hour integration is AB $\gtrsim 32$. This would enable a robust detection of the faintest white dwarfs that could have cooled over the age of the Universe, out to 10 kpc. More than 30 Galactic globular clusters are located within this distance, and therefore a LUVOIR Large Program of a few hundred orbits would achieve high-precision ages for all of them.

[1]http://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap/

A LUVOIR study of white dwarfs in globular clusters is synergistic to both GAIA and LSST. GAIA will target the brightest giants in star clusters to establish much better distances, while LSST will study the periphery of these systems for population studies and dynamics. JWST can also establish high-resolution deep images of cores of globular clusters, but the infrared photometry is not ideally suited for white dwarf studies.

A LUVOIR imaging survey of 30+ globular clusters in the Milky Way will yield the most accurate measurement of the formation time of stars in our Galaxy, and establish a high-fidelity age-metallicity relation based on a method that is independent of stellar chemistry. In addition to the new white dwarf technique, such a survey would *also* provide the highest-precision photometry of the main-sequence population in each cluster to date. If stretched over a wider wavelength baseline from the blue to the red, large gains in the the precision of the main-sequence turnoff could be simultaneously achieved by reducing the error contribution from “fitting” the turnoff feature with stellar models. Therefore, for the first time, two completely independent methods for age-dating stellar populations could be tested over a wide range of metallicity. Not only would this provide *even* more accurate age estimates, but such a uniform comparison of the two methods would yield powerful insights on the validity of stellar evolution models in different parameter space.

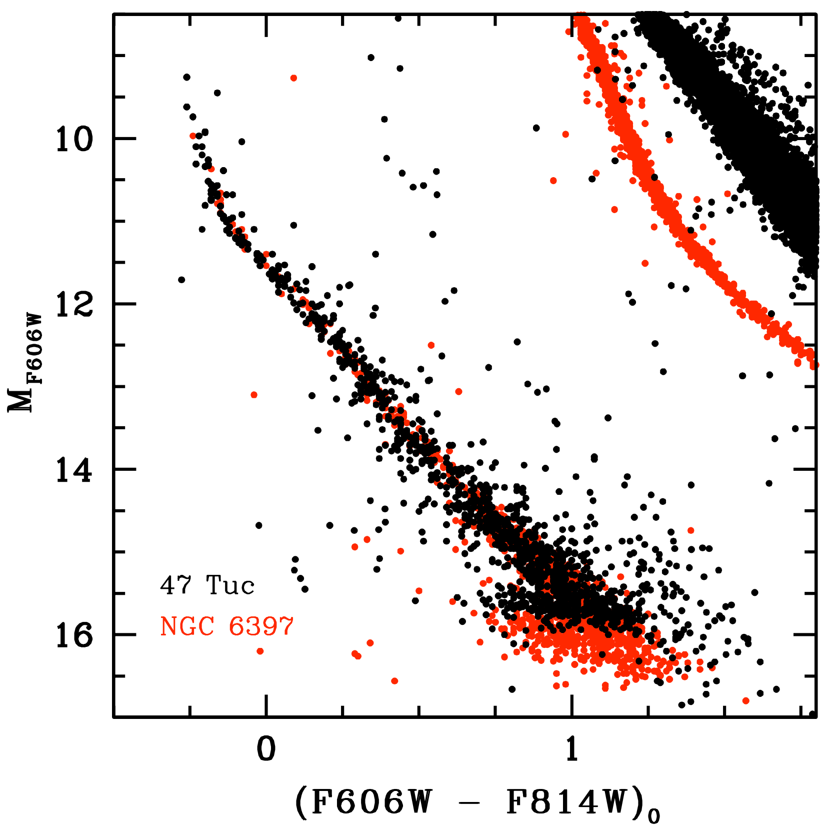


Fig. 1.— The CMD of two nearby globular clusters, NGC 6397 (red) and 47 Tuc (black), as observed in large Hubble Space Telescope imaging projects (Richer et al. 2008 and Kalirai et al. 2012), are superimposed after accounting for differences in distance and reddening. Whereas the stellar main-sequence in the two clusters looks very different due to the different chemical composition (right hand side of Figure), the remnant white dwarf populations sit right on top of another. If imaged with high-precision, these cooling dwarfs provide a very accurate and metallicity-independent age measurement for the cluster. In this case, the NGC 6397 white dwarfs have cooled to a luminosity that is ∼0.5 mag fainter than the 47 Tuc white dwarfs, indicating that NGC 6397 is much older.

References

Bedin, L. R., et al. 2009, ApJ, 697, 965
Beers, T. C., et al. 2012, ApJ, 746, 34
Brodie, J. P., & Strader, J. 2006, ARA&A, 44, 193
Brown, T. M., et al. 2010, ApJL, 725, L19
Bullock, J. S., & Johnston, K. V. 2005, ApJ, 635, 931
Chaboyer, B., et al. 1998, ApJ, 494, 96
Chaboyer, B., & Krauss, L. 2002, ApJ, 567, 45
Chaboyer, B. 2008, IAU Symp., 248, 440
Dotter, A., et al. 2010, ApJ, 708, 698
Dotter, A., et al. 2011, ApJ, 738, 74
Font, A. S., et al. 2011, MNRAS, 416, 2802
Gnedin, O. Y. 2010, IAU Symp 266, 250
Gratton, R. G., et al. 1997, ApJ, 491, 749
Hansen, B. M. S., et al. 2013, Nature, in press
Hansen, B. M. S., et al. 2007, ApJ, 671, 380
Hansen, B. M. S., et al. 2004, ApJS, 155, 551
Kalirai, J., et al. 2012, AJ, 143, 11
Mackey, A. D., & Gilmore, G. F. 2004, MNRAS, 355, 504
Mackey, A. D., et al. 2010, ApJL, 717, L11
Marin-Franch, A., et al. 2009, ApJ, 694, 1498
Richer, H. B., et al. 2008, AJ, 135, 2141
Sarajedini, A., et al. 2007, AJ, 133, 1658
Spergel, D., et al. 2003, ApJS, 148, 175
Vandenberg, D., et al. 1996, ARA&A, 34, 461

Importance of Design Reference Missions for Developing the Next Large Mission Concepts

April 20, 2015

Paul A. Lightsey, Ph.D., Erik Wilkinson, Ph.D.
Ball Aerospace & Technologies Corp

The scientific rationale for the next space-based, large mission is maturing in response to NASA 2020 Decadal Survey preparations (e.g. Cosmic Origins Program Analysis Group (COPAG)). The COPAG has requested white paper community inputs "…for the purpose of commenting on the small set, including adding or subtracting large mission concepts; …for consideration by the NAS Astrophysics Subcommittee". The short list of potential large missions is the Far-IR Surveyor, the Habitable-Exoplanet Imaging Mission, the UV/Optical/IR Surveyor, and the X-ray Surveyor. NASA intends to deliver to the Decadal Survey Committee the science case, straw man design reference mission with straw man payload, technology development needs, and cost requirements assessment.

Science communities are actively assembling and prioritizing the science cases for potential missions. For example, the Associated Universities for Research in Astronomy (AURA) "Beyond JWST" Committee has developed a mission concept called "From Cosmic Origins to Living Earths: The future of UVOIR Space Astronomy". The assessments for these options correctly focus on science themes, the types of observations needed to address those themes including the data quality required, and the notional instrumentation capabilities needed.

Critical to the development of a credible mission concept is to have a well-defined Design Reference Mission (DRM). The development of "straw man design reference mission(s)" as inputs to the NASA Decadal Survey Committee is understood by NASA (AAS Presentation by P. Hertz on preparing for the 2020 Decadal Survey). Ball Aerospace supports this vision and encourages that DRMs be required for mission concepts provided to the 2020 Decadal Survey. A DRMs is a critical tool at the mission level for evaluating potential architectural concepts. Without a well thought out DRM, a conceptual mission design is at risk for not optimizing system trades, identifying necessary technology development, managing resources, and achieving a balanced design.

The DRM should be a set of mission observations that will address the desired science objectives that flow from the science themes defined by the scientific community. Creating the DRM around the science objectives helps to clearly articulate the mission goals, prioritize instrumentation needs, and derive system requirements. For example, the capabilities needed for a broad multi-purpose astrophysics mission have components that are different compared to the more narrowly defined capabilities for exoplanet studies. Developing the DRM provides the tool that in turn is used to develop and evaluate conceptualized mission.

The DRM provides the traceability from science objectives to engineering requirements and can be used to examine options and implications for observations; finding "tall poles" and drivers and identifying the ultimate limits of performance. In this manner, it is a crucial tool for recognizing and nourishing the major strengths of the observatory and ranking design drivers.

The description of the observations within a DRM should include the nature of the targets, the type of data to be obtained, and the necessary quality of the data including:

- Spectral resolution & coverage
  - Driver for detector technologies, coating options, instrument technologies
- Spatial resolution and coverage
  - Driver for aperture shapes and sizes, image quality, fields of view, fields of regard
- Radiometric sensitivity
  - Driver for aperture size, image quality, backgrounds, detector performance
- Radiometric contrast and its spatial dependency
  - Driver for coronagraphy which in turn drives dynamic and thermal stability

The DRM is used as a guide and referee for major "big picture" trades such as orbit selection, schedule availability and scheduling approaches for operations, and time-to-complete the DRM as a metric for observational efficiency. It provides the traceability from science objectives to engineering requirements and can be used to examine options and implications for observations; finding "tall poles" and drivers and identifying the ultimate limits of performance. In this manner, it is a crucial tool for recognizing and nourishing the major strengths of the observatory by understanding the partial derivatives of performance capability. It allows the prioritization of design drivers and risks, and can be used to assessment technology readiness and development needs.

A DRM is used to derive the capabilities that must be provided by the architecture such as:

- Exposure times and completion rates (science based metrics)
- Estimates of data rates and volumes
  - On board data handling and communications requirements for transfer to ground
  - Ground system data handling requirements
- Where to operate
  - What are the environments and how are they conducive to the mission?
    - Availability of science fields and flexibility of scheduling
    - Low background
    - Thermal environment
    - Space environment (radiation, micrometeoroids)
- What is required to operate at that location
  - Attitude control, Station keeping, Communications
- How do you get there?
  - Launch considerations – limits and constraints on architecture

The importance of the DRM in critically evaluating and trading system architectures at the early stages of mission development cannot be understated.

An Evolvable Space Telescope for the Far Infrared Surveyor Mission

C. F. Lillie[a], R.S. Polidan[b] J. B. Breckinridge[c], H. A. MacEwen[d], M. R. Flannery[b] and D. R. Dailey[b]
[a]Lillie Consulting LLC, [b]Northrop Grumman Aerospace Systems, [c]Breckinridge Associates LLC, [d]Reviresco LLC

1. Introduction and overview

In an era of flat NASA budgets, we need to find more affordable ways to build large space telescopes. We believe the root cause for the delay or cancellation of a Flagship class mission is the annual cost of the mission. When development costs consume too large a share of the annual NASA budget-it threatens all other missions, and the science community and NASA must consider drastic measures to reduce the annual cost of the Flagship mission: i.e., schedule extension, down-sizing or cancellation. To be affordable, future flagship observatories must identify and implement new technology AND new development concepts, as well as providing the greatly improved resolution and light collecting power necessary to answer cutting-edge science questions.

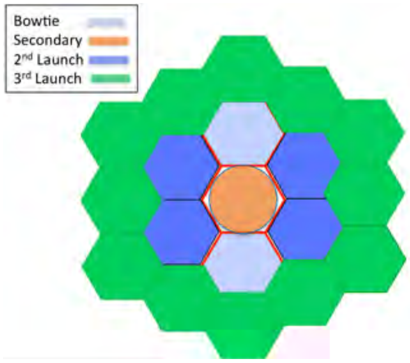
We have been studying observatory architectures where the design, development, construction, and launch of the future large space telescope will be conducted in several stages, each providing a complete telescope fully capable of forefront scientific observations. One approach to building future large space observatories that is intended to break the cost curve and enable large (>10 m) telescopes to be developed within a flat NASA budget is an Evolvable Space Telescope (*Proc. SPIE* 9143-40, Space Telescopes and Instrumentation, 2014). Stage 1 would form the core of the observatory and provide a major improvement over existing observatories operating at the planned launch date. Succeeding Stages would augment the Stage 1 observatory at several year increments (nominally 5 years between launches) by adding additional mirrors, structures, and instruments to the Stage 1 telescope. This approach could be implemented to meet the requirements of three of the four large mission concepts that Paul Hertz has directed the PAGs to consider: i.e., the Far-IR Surveyor, the Habitable-Exoplanet Imaging Mission, and the UV/Optical/IR Surveyor. In this paper we focus on the FIR mission, but also show how UV and exoplanet science questions could be addressed.

2. Key Science Questions

About half of all the energy emitted by stars and galaxies since the Universe began is found in the Far Infrared (FIR) region of the spectrum (~25 to 500 microns). Observations in the FIR thus have great potential for answering fundamental questions about the formation and evolution of our universe, i.e., (1) How did the first stars and black holes in the universe form and evolve; (2) How do massive Black holes in galactic nuclei effect star formation in their host galaxies; (3) How does the FIR spectral energy distribution evolve over cosmic timescales; (4) How do stars of different masses evolve from interstellar clouds to stellar and planetary systems; (5) How do the conditions for planet habitability arise during star, disk and planet formation; and (6) What is the nature of the FIR background? The thermal emission from dust associated with star formation peaks in the FIR, and unique spectral features identify the underlying physics, including the dust particle size, composition, and evolutionary processes in the dense interstellar medium. Fine structure lines in the FIR give information on the temperature balance in these regions; red-shifted features from the mid-IR provide diagnostics for the conditions in galactic nuclei; and hundreds of FIR molecular features, especially simple hydrides, provide unique diagnostics for the build-up of complex organic molecules and water which are important for assessing the habitability of exo-planetary systems. The FIR science possible with future space telescopes has been thoroughly documented in the Far-IR/Sub-mm Community Plans and white papers presented to the National Academy's 2010 survey for astrophysics in the next decade. Key UVOIR and exoplanet science questions have been documented in the ATLAST and AURA HDST study reports.

3. Technical Capabilities

Table 1 describes the engineering concept and the technical capabilities of each of the three stages of a space telescope that would be developed, launched, assembled and operated in the 2030's and beyond. The first Stage telescope would consist of two ~4-m hexagonal mirror segments, a prime focus instrument module and a support structure to separate the instruments from the primary mirror. A sunshield would provide thermal protection for the telescope, and a spacecraft bus would provide the necessary power, communications and attitude control. Stage 2 and Stage 3 components are robotically docked, in cis-lunar space or at L2, in a fashion similar to that commonly used by the space station. At each stage the optical structure is then autonomously aligned to form a working optical telescope.



Parameter	Requirement	Goal	Notes
Telescope Aperture	≥ 10 meters	≥ 16 meters	≥ ATLAST
Stage 1	Bow-tie	4 x 12 m	Two hexagonal segments
Stage 2	Filled Aperture	12 m	Twelve hexagonal segments
Stage 3	Filled Aperture	20 m	Eighteen hexagonal segments
Wavelength	100-2400 nm	0.09-670 μ	UVOIR, Far-IR under evaluation
Field of View	5 to 8 arcmin	30 arc-min	Wide Field VNIR Imaging
Diffraction Limit	500 nm	200 nm	Enhanced UV/Optical resolution
Primary Segment Size	1.97 m	3.93 m	3.93m flat-flat
Primary Mirror Temp	≤ 200K	100K	Minimize heater powe, MIR obs.
Design Lifetime	15 years	> 30 years	On-orbit assembly and servicing

Stage 1 of the EST has a 4 x 12 meter sparse aperture primary mirror and a prime focus instrument module with room for three or four instruments: e.g., a FIR imager and spectrometer, a heterodyne instrument, an Mid-IR imaging spectrometer, a wide field camera for the UVOIR, an exoplanet coronagraph, and a UV spectrometer. Prime focus instruments have the very high transmittance and very low residual polarization characteristic of optical systems with few fold mirrors and near-normal incidence optics that reduce the presence of the unwanted ghost images. The instrument complement for each stage would depend on the science drivers that could be best addressed with 12 x 4-m sparse aperture, a 12-m filled aperture, and a 20-m filled aperture. Note, the Stage 1 telescope can be rotated around its line of sight, and images acquired at roll angles of 0, 60 and 120 degrees can be combined to achieve the spatial resolution of a 12-m filled aperture.
The spatial resolution of the Stage-1 and Stage-2 telescopes will thus range from 0.5 to 10 arc-seconds for the FIR instruments (25-500 microns), 0.1 to 0.5 arc-sec for the mid-IR (5-25 μ), 20 to 100 mill-arc-seconds for the near IR (0.9 to 5 μ), 6 to 20 mas for the Visible (0.3 to 0.9 μ) and 1.9 to 6.3 mas for the UV instruments (0.09 - 0.35μ).

The resolution of the Stage 3, 20-m EST will be 40% better than Stage 2: i.e., 6 arc-seconds at 500 microns. This evolvable telescope will thus have 3.5x and then 5.8x better spatial resolution than Herschel. With a primary mirror temperature of ~100K, the Stages 1 and 2 telescopes will provide ~7 times greater sensitivity than Hershel and the Stage 3 EST will have ~20 times greater sensitivity. We currently envision the installing a larger sunshield for the Stage 3 20-m telescope. It may be possible optimize this telescope for FIR observations by adding one or two more layers to the sunshield and cool the primary mirror to ≥ 40K. At this temperature the telescope would be ~800 times for sensitive than Herschel.

4. Relevance to the Four Mission Concepts

An evolvable telescope architecture is relevant to any normal incidence system including the Far-IR Surveyor, Habitable-Exoplanet Imaging Mission, and the UV/Optical/IR Surveyor.

5. New Technologies

Technology developments needed for a Far-Infrared Surveyor mission are:

- Mirror segments technology at <40kg/m^2 with built-in metrology fiducials in response to a well defined assembly and alignment methodology
- New technology for assembly, maintenance, and servicing of large telescopes in deep space
- Development of Sunshields suitable for 12-m to 20-m space telescopes
- New technology for autonomous alignment of optical structures for space optical systems
- Heterodyne sensors with improved sensitivity
- Improved cooling systems for FIR instruments

6. Are Large Missions Needed?

This evolvable architecture is best applied to a large mission, ultimately providing an affordable ~~a~~ 20-meter aperture, assembled in space over time, using commercial launch vehicles. This architecture is easily scaled to any size large telescope. Utilizing 4-m segments ultimately yields a 20-m filled aperture, while 2-m segments would yield a 10-m filled aperture at Stage 3. Large missions are needed because the characterization of terrestrial exoplanets requires spectra of objects >30th magnitude. Large missions are also needed to provide the sensitivity, spatial resolution and spectral resolution required for a Far-IR Surveyor mission that answers the scientific questions raised by Herschel.

White Paper In Support of a Science and Technical Requirements Study for a UV/Optical/Surveyor in Advance of 2020 Decadal Survey

Definitive Determination of Galaxy Luminosity Functions at Energies Above the Hydrogen Ionization Edge, Covering 11 Billion Years of Evolution

Submitted to the NASA Cosmic Origins Program Analysis Group in Response to a Call for White Papers in Support (or not) of Large Astrophysics Missions to be Studied by NASA Prior to the 2020 Decadal Survey
24 April 2015

Stephan R. McCandliss – Research Professor
Johns Hopkins University
3400 North Charles Street Baltimore, MD 21218
tel 410-516-5272
stephan@pha.jhu.edu

White Paper In Support of a Science and Technical Requirements Study for a UV/Optical/Surveyor in Advance of 2020 Decadal Survey

Science Motivation – The timing and duration of the Epoch of Reionization is crucial to the subsequent emergence and evolution of structure in the universe (c.f. Madau et al. 1999, Ricotti et al. 2002, Robertson et al. 2015). The relative role played by star-forming galaxies, active galactic nuclei and quasars in contributing to the Metagalactic Ionizing Background (MIB) across cosmic time remains uncertain. Deep quasar counts provide some certainty to 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). Moreover, the fraction of ionizing photons that escape from star-forming galaxies (f^e_{LyC}) 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 at redshifts between $12 > z > 6$.

Galaxy luminosity functions at high redshift (Bouwens et al. 2006; Labbe et al. 2010; Gonzalez et al. 2009; Finkelstein et al. 2014) along with a host of assumptions for the clumping factor, the ionizing output and the initial mass function of the first stellar assemblages, have been used to constrain f^e_{LyC} to ~ 0.2, fulfilling the requirement to power the EoR – provided contributions to the LyC from the unobserved population of galaxies at the faint end of the luminosity function are included. Of all these assumptions, the uncertainty in f^e_{LyC} is universally acknowledged as the least understood parameter (Ellis 2014), requiring observation for quantification.

Ionizing radiation escape is a mysterious process. Heckman et al. (2001) have pointed out that mean galactic column densities for H I range from 10^{21} cm^2 for normal galaxies to 10^{24} cm^2 for nuclear starbursts. Yet it only takes a H I column density of 1.6 x 10^{17} cm^2 to produce an optical depth $\tau = 1$ at the Lyman edge. Escape from such large mean optical depths requires that the galaxy interstellar medium (ISM) to be highly inhomogeneous, peppered with low neutral density, high ionization voids and chimneys created by supernovae or the integrated winds from stellar clusters. This implies that escape will be extremely dependent on local geometry, requiring resolutions of star cluster sized structures with typical diameters ~ 30 to 100 pc. Such objects subtend angles of ~ 0.003 to 0.010 arcseconds at redshifts of 2 or 3.

Direct observation of Lyman continuum (LyC) photons emitted below the rest frame H I ionization edge at 911.7 Å becomes increasingly improbable at redshifts $z > 3$, due to the steady increase of intervening Lyman limit systems towards high z (Inoue & Iwata 2008). A key project James Webb Space Telescope (JWST) is to search for those sources responsible for reionizing the universe. However, neither JWST nor the Wide-Field InfraRed Space Telescope (WFIRST), will be able to address the key question of, "How Does Ionizing Radiation Escape from Star Forming Galaxies?"

The far-UV and near-UV bandpasses provide the only hope for direct, up close and in depth, detection and characterization of those environments 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 our key question. Our goal is a definitive determination of L_{900} galaxy luminosity functions over a redshift range from 0 to 3 and will allow us to test whether the escape fraction of low luminosity galaxies is luminosity dependent.

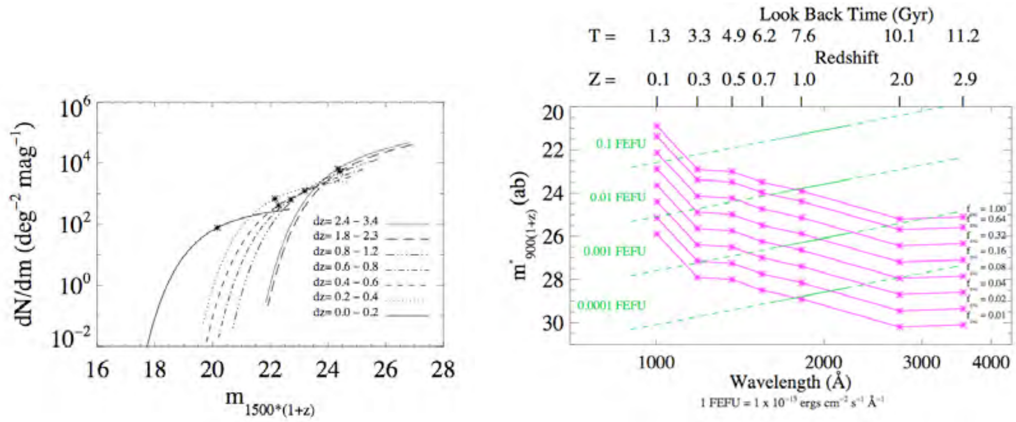


Figure 1 Left panel – Surface densities as a function of observer's frame apparent magnitude for galaxy populations with redshifts between 0 – 0.2, 0.2 – 0.4, 0.4 – 0.6, 0.6 – 0.8, 0.8 – 1.2, 1.8 – 2.3, 2.4 – 3.4, estimated following Arnouts et al (2005). There are 100s – 10,000's of galaxies per square degree. Right panel- 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 defined in the abscissa subtitle.

Observational Requirements – We have undertaken a study (McCandliss et al. 2008; McCandliss 2012) to estimate the flux detection requirements for escaping Lyman continuum photons from star-forming galaxies, as a function of redshift, guided by the galaxy luminosity functions of Arnouts et al. (2005), shown in the left panel of Figure 1. In the right panel of Figure I we provide ionizing continuum flux estimates for "characteristic" (L^*_{UV}) star-forming galaxies as a function of look back time and escape fraction. We find ab-magnitudes for L^*_{UV} galaxies of ~ 30 having escape fractions of 1% between redshift of 2 to 3. We note that the faint end of the higher redshift luminosity functions are ~ 10x fainter than L^*_{UV}, so the detection requirements for the faintest galaxies with similar escape fractions will be 10x lower (although some theorist argue that small galaxies should have high escape fractions).

We will take $f_{900} = 10^{-20}$ erg cm^{-2} s^{-1} $Å^{-1}$ as a representative flux. This is a challenging flux level to reach, requiring a product of effective area, time and bandpass ~ 2.5 x 10^9 cm^2 s Å at 2000 Å to reach a S/N of 5. A telescope with an effective area ~ 15,000 cm^2, observing for ~ 5 hours with either a filter or spectrograph bandwidth of 10 Å can satisfy this requirement, assuming no significant background. Additional requirements include a sample size exceeding 25 objects per luminosity bin per redshift interval to yield an rms deviation of < 20% for each point. The total angular area of the sample should exceed > 1 degree (a the characteristic angular scale BAOs), by a fair margin to beat down cosmic variance. Redshifts are required for each object.

Instrumental Requirements – These observational requirements can be met with a 10 – 12 m class UV telescope with multi-object spectroscopic capability with a spectral resolution of ~ 200 – 1000. The diffraction limit for a 12 m telescope at 2000 Å is ~ 0.003 arcseconds satisfies the spatial sampling requirement. A 2 arcminute wide focal plane at f/24 and 12 m requires a ~170 mm detector FOV. The TRL for such UV detectors and multi-object spectrographs is TRL ~ 5; for 12 m space qualified mirrors diffraction limited at 2000 Å is likely TRL ~ 1. Such a telescope could be compatible with a Habitable-Exoplanet Imaging mission.

PROBING TRANSIENT STRUCTURES IN THE UNIVERSE

Priyamvada Natarajan
Yale University
Submitted to the Cosmic Origins Program Analysis Group (COPAG)

One of the key open and nagging questions in cosmology today is our lack of understanding of the nature of dark matter. Despite the remarkable success of the LCDM paradigm and precision tests of the model, dark matter, the major constituent of all matter in the universe remains elusive. The lack of detection of dark matter particles in the various direct detection particle experiments suggests that either we are yet to understand some critical properties of dark matter aside from clustering and its spatial distribution as a function of scale in the universe that astronomical observations have yielded thus far. There are several aspects of the hierarchical build-up of structure that currently remain unexamined. In particular, the re-distribution of dark matter during mergers and the nature of transient phenomena during these processes are yet to be studied in detail. There are, for instance, several missing pieces in our understanding of the assembly history of clusters of galaxies, the dynamics of in-falling groups and transient structures that form during the merger of sub-clusters. Groups of galaxies appear to be the basic building blocks for large-scale structure and with shorter than Hubble time crossing times, they are dynamic astrophysical laboratories to explore the re-distribution of dark matter and baryons. We now know after detailed cluster studies with HST that in-falling groups are the primarily how clusters build up mass. Current high-resolution studies even with Hubble though have not yet systematically explored the formation mechanisms and kinematic properties of galaxy groups. A large UVOIR space telescope, post-JWST with sub-arc-second resolution (ACS quality or better), combined with a large field of view with a filter set that is blue-through red sensitive will be needed to systematically study groups at high and low redshift with comparable fidelity. Color-selected merging sub-clusters and the bursts of star formation that they produce in addition to lensing signatures of the higher redshift background galaxies need to be followed up systematically. To map and track the fate of dark matter in these transient systems, we need to detect down to a magnitude limit of AB = 29-32, akin to the HST Frontier Fields depths over larger areas of the sky. Transient structures offer the best future window to understanding the true nature of dark matter. As we push imaging deeper to bring into focus higher redshift objects, it is clear that we will start detecting unvirialized objects that are very much in the process of assembling. With precision UVOIR data, we will be able to actually detect and calibrate any offsets between light and mass, i.e. between baryonic matter and dark matter that might provide clues to the true nature of dark matter. This is the next frontier, deeper and wider UVOIR imaging that will reveal the earliest structures that are very much in the process of assembling and prior to virializing. Such transient objects will be found abundantly and characterizing their detailed properties might well reveal the nature of dark matter or catalyze a major rethinking of our conception of dark matter. A deep and wide, space-based UVOIR survey is the future instrument and strategy that are needed to uncover the interplay between baryons and dark matter at the earliest cosmic epochs.

An Evolvable Space Telescope for Future UV/Opt/IR Astronomical Missions

R.S. Polidan[a] J. B. Breckinridge[b], C. F. Lillie[c], H. A. MacEwen[d], M. R. Flannery[a] and D. R. Dailey[a]
[a]Northrop Grumman Aerospace Systems, [b]Breckinridge Associates, LLC, [c]Lillie Consulting LLC, [d]Reviresco LLC

1. Introduction and overview

The Evolvable Space Telescope is a new architectural approach to building future large observatories in space that is intended to break the cost curve and make large (>10 m) telescopes affordable within the flat NASA budget (*Proc. SPIE* 9143, Space Telescopes and Instrumentation , 2014). To be affordable future flagship observatories must identify and implement new development concepts while providing the much improved resolution and light collecting power required to do forefront science. It is our contention that, given the annual funding cycle that NASA must meet, the root cause of the cancellation or delay risks run by a Flagship class mission is the annual cost of the mission. As development costs consume too great a percentage of the annual NASA budget and threaten all other missions, the science community and NASA begin to consider draconic measures to reduce the annual cost of the Flagship mission: e.g., cancellation or program down-sizing and/or extension. There is an alternative approach that enables the development of future large observatories and accommodates NASA's annual budget constraint.

We propose an Evolvable Space Telescope (**EST**) architecture where the design, development, construction, and launch of the future large space telescope will be conducted in a several stages, each providing a complete telescope fully capable of valuable scientific observations. Stage 1 will form the core of the observatory and will perform selected high priority science observations at the initial launch date. Succeeding Stages will build upon the Stage 1 observatory at several year increments (nominally 3 – 5 years between launches), and will add additional mirrors, structures, and instruments to the Stage 1 telescope. This approach can be implemented for any of the normal incidence mission concepts, UV through Far-IR, in the NASA study call.

2. Key Science Questions

Stage 1 of the EST has a 4 x 12 meter sparse aperture primary with an exoplanet coronagraph instrument and/or a starshade and a UV imaging spectrometer located at the prime focus of the telescope. Prime focus instruments have the very high transmittance and very low residual intrinsic polarization characteristic of uncomplicated optical systems with few fold mirrors and near-normal incidence optics to reduce the presence of the unwanted ghost PSF (Breckinridge, J. B., W. T. Lam and R. Chipman, Publ. Astron. Soc. Pacific, **127**, May 2015 – in press). Starshades have higher starlight suppression in the UV so would also benefit from the higher throughput. Wavelength coverage of the coronagraph/starshade system is from 100 to 1000 nm and wavelength coverage of the 2-mirror surface UV spectrometer is 90 to 350 nm. This EST Stage 1 4 x 12 meter telescope provides high angular resolution with a minor signal to noise ratio reduction because of the reduced collecting area of a sparse aperture.
Across the wavelength band the coronagraph has an angular resolution (after processing) of about 10 milliarcseconds at a predicted contrast level of approximately 10^{-9}. UV coronagraphs have the advantage of a relatively narrow inner working angle and access to observing high-energy phenomena such as aurora to understand the role of magnetic fields in planet formation. A magnetic field associated with an exoplanet provides surface protection from high-energy radiation and thus increases the probability of carbon-based life forms. Key science questions for this EST Stage 1 include atmospheric spectra of exoplanets (for example) to characterize water vapor and examine UV absorption of CO. With minimum background polarization to calibrate out precision measurements of Rayleigh scatter in the atmospheres of exoplanets will be possible. Polarization will be useful to discriminate between planetary atmospheres that are clear, have tropospheric clouds or stratospheric haze. Precision polarization measurements from an exoplanet have been shown to be able to reveal information about climate, orbital elements, atmospheric aerosols, surface characteristics, and possibly chemistry.

All aspects of UV Astrophysics, including star and galaxy formation and evolution, the origin of heavy element, gas flows into and out of galaxies, inter-galactic medium composition and structure, dust and molecule formation in stellar winds, and the re-ionization of the universe can also expect major advances from this same EST architecture. The prime focus architecture provides a much higher throughput because of only two reflections prior to entering the science instrument, significantly increasing the effective aperture. Combining this architecture with advanced UV mirror coatings would enable the science community to produce revolutionary UV science discoveries.

EST Stages 2 and 3 are, respectively, filled 12-meter and 20-meter apertures. The science possible with either of these two large telescopes is well known and thoroughly documented in the community.

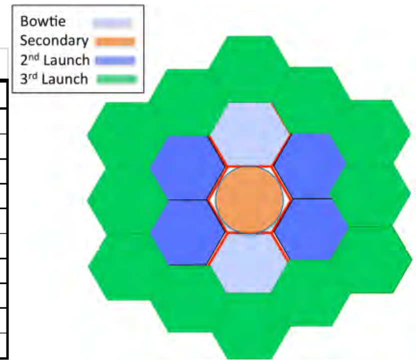
Approved for public release; NGAS Case 15-0798 dated 4/21/15

3. Technical Capabilities

Table 1 describes the engineering concept and the technical capabilities of each of the three stages of the EST. Stage 1 requires the launch of 2 segments and a prime focus instrument assembly along with a metrology structure to separate the mirrors from the prime focus. The Stage 2 and 3 components are robotically docked, in a fashion similar to that commonly used by the space station. At each Stage the optical structure is then autonomously aligned to form a working optical telescope.

Table 1 Design Reference Concept Top Level Requirements

Parameter	Requirement	Goal	Notes
Telescope Aperture	> 10 m	> 16 m	> ATLAST concept
Stage 1	Bow-tie	4 x 12 m	Two hexagonal segments
Stage 2	Filled Aperture	12 m	Six hexagonal segments
Stage 3	Filled Aperture	20 m	Eighteen hexagonal segments
Wavelength	100-2400 nm	90-8000 nm	UVOIR, MIR under evaluation
Field of View	5 to 8 arcmin	30 arcmin	Wide field VNIR imaging
Diffraction Limit	500 nm	250 nm	Enhanced UV/Optical resolution
Primary Segment Size	2.4 m	3.93 m	flat to flat
Primary Mirror Temp	< 200 K	150 K	Minimize heater power
Design Lifetime	15 years	>30 years	On-orbit assembly and servicing



4. Relevance to the Four Mission Concepts

The EST architecture is relevant to any normal incidence system including the Far-IR Surveyor, Habitable-Exoplanet Imaging Mission, and the UV/Optical/IR Surveyor.

5. New Technologies

Technology developments needed for EST are:

- To take advantage of the prime focus design for UV imaging and spectroscopy, UV coatings with high reflectivity from 90 to 300 nm and UV-VIS coatings with uniform and high phase and amplitude reflectivity having minimum residual polarization are required.
- Development of starlight suppression systems to enable imaging of exoplanets
  - Development of Starshade starlight suppression systems suitable for large telescopes
    - Architectures capable of deploying ~60 m starshades
    - Formation flying sensors and algorithms necessary for maintaining alignment
  - Innovative coronagraph architectures
    - Coronagraphs that employ elements low internal polarization and nano-structured masks and stops to control the complex field and enable terrestrial-exoplanet contrast levels at the 10^{+10} levels. Innovative designs to radially achromatize coronagraphs are needed for broad-band performance.
    - Coronagraph architectures desensitized to telescope system vibration with innovative, high performance WFSC systems optimized for coronagraphy.
- Mirror segments technology at <40 kg/m^2 with built-in metrology fiducials in response to a well-defined assembly and alignment methodology
- Technology for robotic assembly, latching, maintenance, and servicing of large telescopes in deep space
- Technology for autonomous precision alignment and wavefront control of optical elements for space telescopes

6. Large Mission Needed?

The EST architecture is best applied to a large mission, ultimately providing an affordable 20-meter class aperture, assembled in space over time, using moderate size launch vehicles. The EST architecture is easily scaled to any size large telescope. Utilizing 4 meter segments ultimately yields a 20 meter filled aperture, whereas utilizing 2 meter segments would yield a 10 meter class filled aperture at Stage 3. Large missions are needed because the characterization of terrestrial exoplanets requires spectra on objects >30^{th} magnitude. Large apertures are required to collect enough photons for a reasonable integration time and to control unwanted radiation at the required very narrow inner working angles. We propose that studies of future large normal incidence astrophysics missions explore using the Evolvable Space Telescope architecture outlined in this white paper as their baseline approach.

A Rotating Synthetic Aperture (RSA) Space Telescope for Future UV/Opt/IR Astronomical Missions

Ronald S. Polidan, Amber Bauermeister, Northrop Grumman Aerospace Systems
Gerard Rafanelli, Mitchell Haeri, Raytheon Space and Airborne Systems

1. Introduction and overview

Observatory aperture size is a key performance-driving parameter for current high-priority astrophysics missions. Large apertures provide high resolution and large light-gathering power; key observatory parameters for the imaging and spectroscopy of faint, distant celestial objects. The limitations of current technologies drive the launch and development costs of large filled-aperture space telescopes. This is due to mass, complexity, launch vehicle fairing volume and the high cost of traditional deployed adaptive optics designs. With filled-aperture designs, the "next big thing" in astrophysics may wait a long time as space telescope and launch vehicle technologies mature. This whitepaper explores an alternate architecture based on current technologies that would provide the resolution of a ~20 m aperture while retaining the mass, cost, and photon throughput of an 8 to 9 m aperture.

Over the last two decades the U.S. government, Northrop Grumman, and Raytheon have invested substantially in a revolutionary non-traditional space telescope architecture that can be deployed today. Elements of Raytheon's "SpinAp" architecture are disclosed in several patents. The architecture is based upon a Rotating Synthetic Aperture (RSA) that synthesizes very large circular apertures at a fraction of the complexity, mass and cost. The 10m SpinAp optic, or even larger spin aperture, can address current astrophysics priorities with today's mature, demonstrated technologies and a single launch to orbit (Figure 1). Assuming mirror mass fraction is proportional to fill factor, for a given aperture, the required mirror mass can be reduced by up to 75% by utilizing the RSA architecture instead of a filled aperture. Reduced mass translates to reduced cost for the optical telescope assembly, spacecraft accommodation, and launch vehicle. Reduced mass also enables scientific missions that would otherwise require many years of technological development or multiple launches. A conceptual RSA Observatory reference design and comparative performance parameters for Hubble, JWST and 12 m filled designs are shown in Figure 2.

Figure 1. "The Universe in High-Definition" can be obtained today using a Rotating Synthetic Aperture (RSA) space telescope

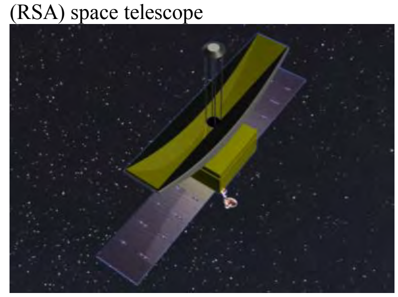


Figure 2. Space Telescope Sensitivity and Resolution Comparison

Telescope Parameter	Hubble Space Telescope	James Webb Space Telescope	12 m Filled Circular Aperture	16-20m RSA (18m x 3m)
Diameter	2.4 m	6.5 m	12 m	16-20 m
Collecting Area	4.5 m^2	25 m^2	113 m^2	50-64 m^2
Angular Resolution[a] (500 nm)	0.05"	0.02"	0.011"	.0063 -.0079" [b]
Angular Resolution[a]: NIR (2 μm)	0.2"	0.08"	0.042"	.031-.025" [b]

[a] Diffraction-limited angular resolution for a filled circular aperture of the given diameter
[b] Linear synthesis processing results in an angular resolution equivalent to a filled circular aperture. Nonlinear processing of SpinAp data will provide 20% better resolution than an equivalent filled circular data set processed with the same algorithms.

We propose that studies of future large normal incidence astrophysics missions (the Far-IR Surveyor, Habitable-Exoplanet Imaging Mission, and the UV/Optical/IR Surveyor) explore using the RSA as their core architecture.

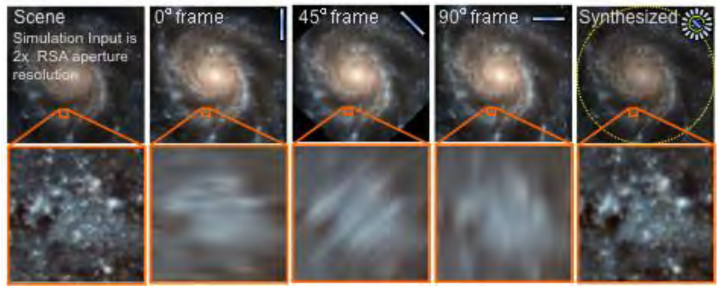
2. Key Science Questions

The key science questions addressed by the RSA architecture are those of any large (> 8 m) filled aperture telescopes. RSA offers a different way to build and use the telescope. It offers the collecting area of an 8 to 9 meter telescope with the resolution (after data processing) of a telescope twice that size.

3. Technical Capabilities

How a Rotating Synthetic Aperture Works Using a 20 meter, 8:1 aspect ratio, RSA as an example that balances aperture (16% fill factor) and resolution (6.3 milliarcsec at 500 nm, this design would provide the resolution of a 20 m aperture while retaining the mass, cost, and light-gathering power of an 8m aperture. Figure 3 simulates a notional imaging sequence for this example design. The HST-derived input scene at left is 2x the resolution of the 8:1 RSA high resolution cutoff. As the telescope rotates it acquires imagery with a two dimensional detector array. The individual frames depicted in Figure 3 all have the same field of view. Each frame measures the spatial frequency information associated with the rectangular aperture. At the completion of an 180° rotation, with appropriate angular sampling by the individual frames, all spatial frequencies associated with a filled aperture measurement of the scene have been measured, yielding the rightmost frame in Figure 3. This processing chain has been fully demonstrated and has the ability to obtain further resolution enhancement with optimal nonlinear processing.

Figure 3. A synthesized RSA observation of M101 (HST image). In the simulation the 20 m RSA acquired 80 frames over a 180 degree rotation. Synthesis processing results in the image at right.



RSA Architectures and Integration Times Integration times for RSA are increased relative to a filled circular system with the same effective diameter. The RSA design provides an integration time penalty inversely proportional to the *square* of the fill factor, versus the *cube* for dilute and sparse apertures, greatly improving mission capability. RSA is a very flexible architecture: the total integration time, frame integration time and image resolution can be balanced using the mirror aspect ratio to achieve the desired mission science performance. Figure 4 provides key performance parameters for three RSA aspect ratios.

Figure 4. RSA Parameters for a Range of Aspect Ratios

Rotating Synthetic Aperture Parameters					12 m Aperture Comparison		Diameter of filled aperture with equivalent light gathering capability (m)
Aspect Ratio	Mirror Length (m)	Mirror Width (m)	Mirror Area (m^2)	Vis (500 nm) Angular Res. (milli-arcsec)	RSA Fill Factor	RSA Integration Time factor	
4:1	16	4	64	7.86	56.6%	3.12	9.03
6:1	18	3	54	6.99	47.7%	4.39	8.29
8:1	20	2.5	50	6.29	44.2%	5.12	7.98

4. Relevance to the Four Mission Concepts

The RSA architecture is relevant to any normal incidence system including the Far-IR Surveyor, Habitable-Exoplanet Imaging Mission, and the UV/Optical/IR Surveyor.

5. New Technologies

Much of the core technology needed to enable RSA has already been developed by industry and other government agencies. Multiple trade studies are needed to assess the value of RSA for astrophysics but the new technologies needed for RSA are only those that convert the current RSA concept into an astrophysical observatory:

- Development of starlight suppression systems (starshade and/or coronagraph) to enable imaging of exoplanets
  - Starshade starlight suppression systems suitable for RSA sized telescopes: architectures capable of deploying ~60 m starshades, formation flying sensors/algorithms for maintaining alignment to the starshade.
  - Innovative coronagraph architectures: designs that can accommodate the RSA point spread function and are insensitive to telescope system vibration with innovative WFSC systems optimized for coronagraphy.
- Thermal, vibrational, and pointing control technologies to satisfy astrophysics mission requirements.
- Detector technologies that optimize astrophysics mission performance for the rectangular RSA primary mirror and can achieve the low noise performance necessary to image faint objects.

6. Large Mission Needed?

The RSA architecture is best applied to a large mission and will provide a more affordable path to building the next great observatory. The RSA approach can provide an affordable ~9 meter telescope with "super-resolution" to address the highest priority science goals.

The Origin of the Elements Heavier than Iron

A white paper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

Ian U. Roederer, Dept. of Astronomy, U. Michigan, Ann Arbor, MI (iur@umich.edu)

Jennifer S. Sobeck, Dept. of Astronomy, U. Virginia, Charlottesville, VA (jsobeck@virginia.edu)

James E. Lawler, Dept. of Physics, U. Wisconsin, Madison, WI (jelawler@wisc.edu)

April 24, 2015

1. Key Science Questions— Understanding the origin of the elements is one of the major challenges of modern astrophysics. What are the physical mechanisms, conditions, and sites where heavy elements are produced? 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 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 characterize 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 15 elements (including Ge, As, Se, Cd, Te, Lu, Ta, W, Re, Os, Ir, Pt, Ag, Hg, 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).

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. Yet, many interesting stars lie at distances too great for practical observations with HST+STIS or COS, including stars with the highest levels of r-process enrichment, stars with severe deficiencies of r-process and s-process material, and stars with unexplained deviations from the r-process and/or s-process abundance patterns.

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), Roederer & Lawler (2012, Astrophys. J., 750, 76), and Roederer et al. (2014, Astrophys. J., 791, 32).

2. Technical capabilities— The spectral region between 1900 Å and 3100 Å contains dozens of neutron-capture absorption lines that have been demonstrated to be good abundances indicators. Useful lines are widely spaced from 1900 Å to 3100 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 $\mathrm{km\,s^{-1}}$) 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. Experience shows that S/N $\sim$ 50–100 after co-adding multiple exposures is sufficient to achieve the science objectives.

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 objectives.

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. If this feature is available, investigators would, of course, try to identify stars of interest that could be observed simultaneously. However, such considerations should be a secondary concern, at best, in the instrument design.

3. Relevance of the four mission concepts— The UV/Optical/IR Surveyor mission concept has the potential to meet the science objectives and technical capabilities described in this white paper. Neither JWST, WFIRST, nor any of the other mission concepts is likely to offer the combination of sensitivity and spectral resolution at the UV wavelengths of interest.

4. New Technologies— Unknown to us at this time.

5. Large Mission Needed?— The high S/N ratios and spectral resolution needed to accomplish these science goals on faint targets require a large collecting area, so this almost certainly requires a flagship-sized mission.

The First Stars and the First Metals

A white paper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

Ian U. Roederer, Dept. of Astronomy, U. Michigan, Ann Arbor, MI (iur@umich.edu)

Anna Frebel, Dept. of Physics and Kavli Institute for Astrophysics and Space Research, MIT, Cambridge, MA (afrebel@mit.edu)

Timothy C. Beers, Dept. of Physics and JINA Center for the Evolution of the Elements, Univerisity of Notre Dame, Notre Dame, IN (tbeers@nd.edu)

April 24, 2015

1. Key Science Questions— The nucleosynthetic signatures of the first stars and supernovae are imprinted on the atmospheres of the most metal-poor stars found today. What were the properties (e.g., masses, rotation rates, binary fractions) of these first Pop III stars, where were they formed, and what were their supernovae explosions like? These critical science questions, and others, can be addressed by studying the compositions of surviving second-generation stars that formed from the ISM polluted by metals produced by these Pop III stars. 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, and how galaxies and their constituent stars formed and evolved.

Six stars with Fe abundances less than $10^{-4.5}$ times the Solar abundance (i.e., [Fe/H] < -4.5) are known at present (Christlieb et al., 2002, Nature, 419, 904; Frebel et al., 2005, Nature, 434, 871; Norris et al., 2007, ApJ, 670, 774; Caffau et al., 2011, Nature, 477, 67; Keller et al., 2014, Nature, 506, 463; Hansen et al., 2014, ApJ, 787, 162). More are expected to be found among ongoing and future surveys (e.g., LAMOST, SkyMapper). One of the striking characteristics of five of these six stars is the high level of C, N, and O abundances relative to Fe (e.g., $+1 <$ [C/Fe] $< +4$). This suggests that a particular class of "faint" supernova with low explosion energies may have been relatively common in the early Universe (e.g., Iwamoto et al., 2005, Science, 309, 451; Meynet et al., 2006, A&A, 447, 623; Heger & Woosley, 2010, ApJ, 724, 341; Ishigaki et al., 2014, ApJL, 792, L32). Rapidly-rotating massive stars have been proposed as an alternative explanation (Maeder et al., 2015, A&A, 576, A56).

One critical—but, in principle, surmountable—challenge in studying these metal-poor stars is the lack of elements that can be detected. Only a few tens of absorption lines are commonly found in the optical spectra of these stars, so only $\approx$ 5–10 elements are regularly detected.

Many others (Be, B, Si, P, S, Sc, V, Cr, Mn, Co, Ni, and Zn) are expected to be present but are rarely detected, and the upper limits derived from their non-detections are often uninteresting.

The UV spectrum is an unexplored window that would allow all of these elements to be detected if present in the most metal-poor stars known. The challenge is that the known stars are much too faint for high-quality observations with HST, and the stars expected to be found in future surveys are likely to be as faint as these or fainter. A single UV spectrum would double or triple the number of elements detected in any of these stars, and observations of all such stars would revolutionize our understanding of the first stars, the first supernovae, and the first metals in the Universe.

2. Technical capabilities— The spectral region between 1700 Å and 3100 Å contains hundreds of potentially useful lines of elements from Be ($Z = 4$) to Zn ($Z = 30$). These lines are widely spaced from 1700 Å to 3100 Å, so a UV 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, and $R \sim 30{,}000$ is the minimum acceptable resolution. Typical S/N goals would be $\sim$ 50–80 after co-adding multiple exposures.

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 or HST+COS at these wavelengths. This would enable studies of about half of the most metal-poor stars known at present (red giants at distances up to $\sim$ 6 kpc, and subgiants at distances up to $\sim$ 2.5 kpc) and similar stars discovered in future surveys. Even greater overall throughput (a factor of $\sim$ 100 improvement over HST) would be needed to study the other known stars and many of those expected to be found by surveys in the next several decades. Multiplexing offers no scientific advantage since the field density of the most metal-poor stars is, and will likely remain, $\ll 1$ star deg^{-2} to $B \lesssim 18$.

3. Relevance of the four mission concepts— The UV/Optical/IR Surveyor mission concept has the potential to meet the science objectives and technical capabilities. Neither JWST, WFIRST, nor any of the other mission concepts is likely to offer the combination of sensitivity and spectral resolution at the UV wavelengths of interest.

4. New Technologies— Unknown to us at this time.

5. Large Mission Needed?— The high S/N ratios and spectral resolution needed to accomplish these science goals on faint targets require a large collecting area, so this almost certainly requires a flagship-sized mission.

HabX2: a 2020 mission concept for flagship science at modest cost

A White Paper submitted in response to the CoPag call for input on 2020 decadal science and mission concepts

M. Swain (JPL), S. Redfield (Wesleyan), D. Fischer (Yale), M. Marley (ARC), T. Greene (ARC), N. Cowan (Amherst), C. Griffith (LPL), Y. Yung (Caltech), A. Mandell (GSFC), C. Lawrence (JPL), J. Rhodes (JPL), A. Kiessling (JPL), C. Martin (Caltech), G. Vasisht (JPL), C. Beichman (IPAC), O. Doré (JPL)

Philosophy: We will develop a flagship mission concept driven by compelling exoplanet science and important general astrophysics capability, of a scope and cost that leaves space in the NASA program for other astrophysics missions. Our approach is to maximize the science per dollar in a cost-capped environment using a single science theme to drive design. We see this activity as necessary and complementary to study efforts considering larger, more broadly focused flagship missions.

Starting Point: The central design question is what is the maximum habitable planet science that can be realized for a cost at various points in the range $2–$5 billion. We take as a starting point (hereafter"HabX2") a concept designed for direct imaging of Earth analogs *and* transit spectroscopy of M-dwarf habitable zone worlds. One key to controlling cost is to focus on implementation simplicity; the baseline concept is a stable, 3 m or larger, 280-200 K telescope, operating at L2 for 10+ years, with two spectroscopic measurement modes, one for direct imaging spectroscopy in the visible and near-IR with R~200, and one for continuous spectral coverage between ~200 nm and ≤5 μm (determined by the telescope temperature) with R~300-3000. To ensure responsiveness to the most important scientific priorities, and to leverage ongoing technology development efforts, implementation of the direct imaging spectroscopy mode as an "internal" or "external" occulter would be determined during prephase A development. Direct imaging spectroscopy would be the design driver for HabX2, with the continuous spectral coverage capability being implemented in a non-design-driving role. Ultra-light-weight mirror technologies, off-axis telescope implementations, and a range of telescope sizes, will be considered. We will evaluate the trade-off between mirror stability, telescope temperature, and longest wavelength not limited by the thermal background of a warm telescope, and also allowing the telescope to cool during the post-prime mission phase to enable spectroscopy from the near-IR to 5 μm. MCT detectors capable of working between 700 nm and 5 μm require only passive cooling.

Science: The exoplanet science case is centered on answering the over-arching question: ***Do temperate, terrestrial worlds outside of our solar system possess conditions that could support life?*** To answer this requires spectroscopic measurements of terrestrial exoplanet atmospheres; for this task, the HabX2 concept offers two important measurement capabilities.

- Direct Imaging Spectroscopy – This capability would allow both searching for and spectral characterization of temperate, terrestrial, habitable zone planets around nearby stars including potential detection of the O_2 and H_2O bands and imaging disks and planets in young planetary systems. The combination of a stable, optimized telescope and optimized implementation of the internal/external occulter would provide performance enhancements to build on the successes of WFIRST/AFTA.
- Transit Spectroscopy – In the post-JWST era, HabX2 would provide a critical capability to study atmospheres of T^3 (temperate, terrestrial, transiting) planets, with broad, continuous spectral coverage and repeated observations of long period

systems. T[3] planets, found by K2, TESS, and Plato, will be an important aspect of addressing the question of exoplanet habitability. The NIR capability provides access to deeper, broader molecular bands of CH_4, CO, and CO_2. Additionally, the transit spectroscopy capability of HabX2 will enable the study of atmospheric properties and processes of a wide variety of planets, which both enables comparative exoplanetology, and provides a context to better understand the atmospheric processes on potentially habitable worlds.

The HabX2 continuous spectroscopy capability from the UV to the IR is a versatile instrument with a wide range of science objectives ranging from probing the cosmic web to following up LSST (and other large survey) identification of transient and rare objects at low to high z. For example, the time domain and astrophysical spectroscopy capability of HabX2, extending into the UV, offer an important follow-on to Euclid and WFIRST by allowing pointed observations of specific targets found via those wide-field surveys. High NIR backgrounds will limit the capability of ground-based follow up of astrophysically interesting sources, meaning that the capabilities of HabX2 will play an important role in galaxy evolution studies in the 2030s. HabX2 will also be a key instrument in ongoing dark energy, dark matter, and galaxy evolution work in the post Euclid/WFIRST/JWST era.

We intend to undertake a vigorous study of the HabX2 concept with the objective of answering the following questions:

- What is the minimum mission cost for HabX2 that will answer the question: *Do temperate, terrestrial worlds outside of our solar system possess conditions that could support life?* In exploring this, we will create science merit functions and explore a range of mission architectures and notional design reference missions.
- What is the relationship between science grasp and cost in the $2 to $5 billion mission price range?
- What are the most compelling science cases, both exoplanet and general astrophysics, for a mission of this type in the post JWST, post WFIRST/AFTA world?
- What is the technology roadmap to implement HabX2?

The field of exoplanets is developing rapidly. Assumptions, including the basic one that temperate, terrestrial worlds are the best place to look for life, must be re-examined periodically as new data and new understanding develop.

In undertaking this study, we anticipate working with partners in NASA, academia, FFRDCs, and industry; our work will build on and complement the recently completed Exo-S and Exo-C studies by NASA's ExEP.

Listening to the Cosmic Dawn

Ira Thorpe[1], Robin Stebbins, John Baker,
Jeffrey Livas, Jeremy Schnittman, John Mather
NASA Goddard Space Flight Center

Daniel Holz
University of Chicago

Scott Hughes
Massachusetts Institute of Technology

Guido Mueller, John Conklin
University of Florida

Neil Cornish, Nicolas Yunes
Montana State University

Peter Bender
University of Colorado

Douglas Richstone
University of Michigan

Curt Cutler, Michele Vallisneri
NASA Jet Propulsion Laboratory

Matthew Benacquista
University of Texas Rio Grande Valley

Shane Larson, Tyson Littenberg
Northwestern University

Cole Miller
University of Maryland

Emanuele Berti
University of Mississippi

Ryan Lang
University of Illinois

[1] james.i.thorpe@nasa.gov

Summary

Structure formation has led to a great many mergers of galaxies and their massive black holes. A space-based gravitational wave observatory with sensitivity in the millihertz band will detect and measure these events over a wide range of masses and redshifts, providing information on the formation and evolution of massive black holes and the galaxies in which they reside. The observational capabilities in the gravitational-wave spectrum are complementary to those in the electromagnetic spectrum and will provide unique answers to COPAG's Big Question: "How did the universe originate and evolve to produce the galaxies, stars, and planets we see today?"

1. Key Science Questions[2]

A space-based gravitational-wave (GW) observatory such as the proposed *Laser Interferometer Space Antenna (LISA)* will **probe massive black holes over a very wide range of redshift, covering essentially all important epochs in their evolutionary history.** This will offer a unique, new way to address a number of unanswered questions:

- *Did the first black holes form in pre-galactic halos? What was their initial mass and spin?*
- *What is the mechanism of black hole formation in galactic nuclei? How do black holes evolve over cosmic time due to accretion and mergers?*
- *How did hierarchical galaxy assembly proceed in detail?*

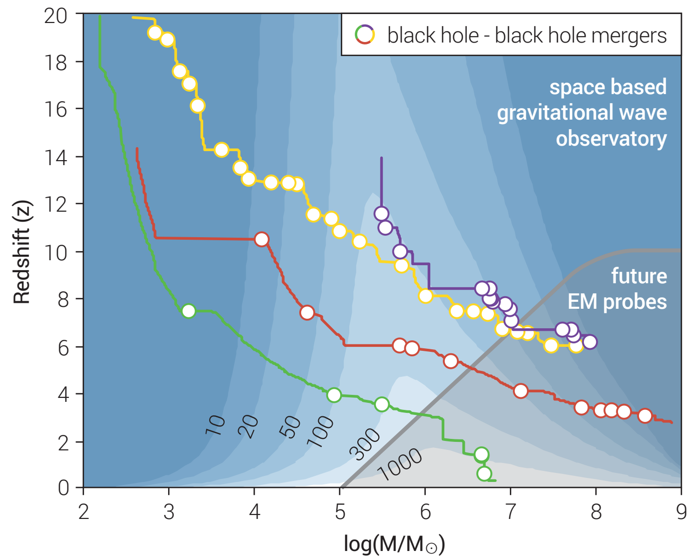


Figure 1: A space-based GW observatory will detect and characterize massive black hole mergers over a wide range of masses and redshifts, as indicated by the shaded contours showing GW SNR for the eLISA mission concept. As individual supermassive black holes evolve (colored tracks), they will undergo multiple mergers (open circles) that will be observed in GWs. A space-based GW observatory will be most sensitive to black hole mergers at higher redshift and lower mass than the black-hole-powered phenomena likely to be observed by future electromagnetic observatories (gray shaded region). (Adapted from Figure 2 of [1]).

Gravitational waves provide an exquisite probe for addressing these questions. Because each signal is emitted and detected in full coherence, sensitivity falls off only as 1/R, not $1/R^2$. Thus, LISA will track the merger history of massive black holes from the first seeds at redshifts of ≳20 through major mergers in the local universe using gravitational wave observations alone. As shown in Figure 1, black hole mergers with masses in the interval between 10^4 $M_\odot$ and 10^7 $M_\odot$ will be observed with significant signal-to-noise (SNR), allowing the individual masses, spins, and luminosity distances of the merging black holes to be precisely measured. **The range of black hole masses and redshifts sampled is complementary to that of black-hole-powered phenomena likely to be observed by future electromagnetic observatories.**

LISA will have all-sky sensitivity, making it a survey mission. In fact, **LISA will provide the widest and deepest survey of the universe ever produced**. LISA will detect the vast majority of all merging massive black hole binaries, even when the black holes are not electromagnetically active. This will expose an unseen population of objects which will potentially carry precious information about the black hole population as a whole. This comprehensive survey will enable investigation of the link between the black hole seed population and the rich population of active supermassive black holes observed

---

[2] Adapted from Chapter 1 of [1]

electromagnetically. LISA's measurements of black hole spins will provide information on whether early accretion flows were chaotic or coherent. Gravitational wave observations alone will be able to distinguish between the different massive black hole formation and evolution scenarios.

In a five year baseline mission, LISA should observe 100-250 massive black hole mergers, in addition to 800 extreme-mass-ratio inspirals and 40,000 close compact binaries in the Milky Way. For most of these sources, LISA will track the phase evolution of these millihertz signals for months to years.

2. Technical Capabilities

In *New Worlds, New Horizons*, the 2010 decadal prioritized the LISA mission and its associated science [2] after WFIRST. The capabilities of that mission or a close relative could achieve the science described here. Adjusting mission parameters such as constellation size, number of arms, telescope size, laser power, operational orbit, drag-free performance, and operational lifetime will affect the numbers of black hole mergers observed and the precision of their measured masses, spins, and sky locations.

3. Relevance of The Four Mission Concepts

A space-based gravitational wave observatory, such as the *Gravitational Wave Surveyor* found in the *Enduring Quests, Daring Visions* roadmap document, was not included in the proposed list of four mission concepts, because the NASA Astrophysics Division is pursuing a minority role in the L3 launch opportunity of ESA's Cosmic Vision Programme. ESA has already selected "The Gravitational Universe" as the science theme. The notional mission concept for L3 is significantly reduced from the LISA concept that has previously been reviewed and endorsed by NRC reviews. These changes will affect the science case, cost, and risk of the resulting mission. **A study is needed to evaluate levels of US participation in a European mission, and the associated science, cost, and technology development activities.** Because LISA has been so thoroughly studied in the past, this study can be more focused than the mission concept studies envisioned by the memo from Paul Hertz and could occur in parallel but must begin soon in order to meet the L3 timetable. **We're seeking COPAG endorsement for this study of a mission that can do unique and important Cosmic Origins science.**

4. New Technologies

More than two decades of sustained effort on the LISA project in the US and Europe has produced a mission concept and associated technologies that are highly mature. Of particular significance is the **upcoming launch of the LISA Pathfinder technology demonstrator mission in the Fall of 2015**. However, it is worth noting that European leadership in LISA Pathfinder has led to much of the expertise in key technical areas being dominated by European institutions. Should the US play a significant role in a future GW mission, it will be necessary to sustain and expand US technical and scientific capabilities.

5. Large Mission Needed?

The question of whether the NRC-endorsed science of the LISA mission could be carried out in part by a probe class mission was a key question of a 2011 NASA-sponsored study that consisted of a collection of mission concepts and technologies from the community, technical and cost assessments of each concept, and three full-scale mission concept studies. The final report [3] concluded that no viable concept capable of returning *any* of the LISA science case had a cost <$1B. However, an international partnership such as a minority role in L3 could reduce the NASA cost to well below that level.

References

[1] K. Danzmann, et al. *The Gravitational Universe,* available at https://www.elisascience.org/dl/TheGravitationalUniverse.pdf (2013)

[2] LISA Mission Science Office, *LISA: Probing the Universe with Gravitational Waves*, LISA Project internal report number LISA-LIST-RP-436 (March 2009), available at http://lisa.gsfc.nasa.gov/documentation.html.

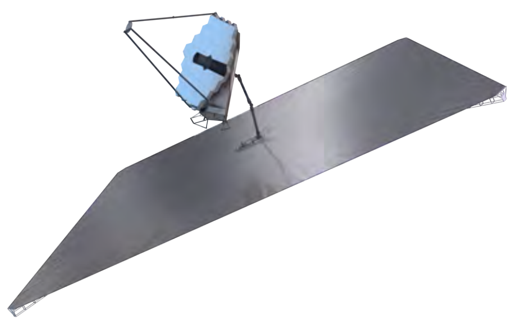
[3] K. Anderson, R. Stebbins, R. Weiss, E. Wright, et al. *Gravitational Wave Mission Concept Study - Final Report*, available at http://pcos.gsfc.nasa.gov/physpag/GW_Study_Rev3_Aug2012-Final.pdf (2012)

Continuing the Legacy of the Hubble Space Telescope

A Large-Aperture UVOIR Space Telescope

H. A. Thronson (NASA GSFC), M. Clampin (NASA GSFC), M. Postman (STScI),
D. Redding (NASA JPL), & H. P. Stahl (NASA MSFC)
Point of Contact: Harley.A.Thronson@nasa.gov
May 1, 2015

Overview: A large-aperture (~10+ m) non-cryogenic UVOIR space observatory that builds upon engineering elements and technologies developed for JWST will achieve major science goals highlighted by both the Cosmic Origins and Exoplanet Exploration Program Analysis Groups, as well as some goals of the Physics of the Cosmos Program Analysis Group (PAG). The priority science goals for such a mission have been identified by the NASA 30-year astrophysics roadmap, *Enduring Quests, Daring Visions*, and the soon-to-be-released AURA *From Cosmic Birth to Living Earths* report. Here we summarize the key design characteristics of the mission.



Conception of our current reference design for the Advanced Technology Large-Aperture Space Telescope (ATLAST) version of LUVOIR. [NASA image]

Reference Design: This figure shows a visualization of our ATLAST reference design, a 9.2-meter diameter segmented aperture capable of being launched by existing EELV vehicles. The basic design is capable of being expanded to apertures as large as ~14 m pending availability of suitable launch vehicles (i.e., SLS with larger fairings than Block 1). This concept builds on design solutions, technologies, engineering and lessons learned from JWST and other recent and ongoing projects, as well as growing experience with ground-based segmented telescopes. This version utilizes the JWST "chord-fold" deployment approach, which we estimate can be extended to launch an aperture of ~12 m using the EELV shroud volume. Unlike JWST, however, it will operate at "room temperature," thus avoiding costly and complex cryogenic design, fabrication, testing, and integration.

Mission Design Requirements: The mission design requirements flow-down from top-level science goals.

Science requirements flow-down to telescope

Parameter		Requirement	Stretch Goal	Traceability
Primary Mirror Aperture		≥ 8 meters	12 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope Temperature		273 K – 293 K	-	Thermal Stability, Integration & Test, Contamination (UV), IR Sensitivity
Wavelength Coverage	UV	100 nm – 300 nm	90 nm – 300 nm	
	Visible	300 nm – 950 nm	-	
	NIR	950 nm – 1.8 μm	950 nm – 2.5 μm	
	MIR	-	Sensitivity under evaluation	
Image Quality	UV	< 0.20 arcsec at 150 nm	-	
	Vis/NIR/MIR	Diffraction-limited at 500 nm	-	
Stray Light		Zodi-limited between 400 nm – 1.0 μm	Zodi-limited between 200 nm – 1.8 μm	Exoplanet Imaging & Spectroscopy SNR
Wavefront Error Stability		< 10 pm RMS uncorrected system WFE per control step	-	Starlight Suppression via Internal Coronagraph
Pointing	Spacecraft	≤ 1 milli-arcsec	-	
	Coronagraph	< 0.4 milli-arcsec	-	

Starlight Suppression: ATLAST is designed to be a general astrophysics observatory capable of breakthrough science in many areas. However, some of the most challenging design requirements will be imposed by the goal of also being able to detect biomarkers in the UVOIR spectra of Earth-like worlds in the solar neighborhood. Our concept uses an internal coronagraph for starlight suppression, exploiting ongoing progress by the WFIRST/AFTA Coronagraph Project in developing designs that provide high contrast, even with complex, obscured apertures. Use of deformable mirrors within the coronagraph will correct static telescope aberrations from the visible-light diffraction limit, shaping the wavefront to the picometer precision needed for extremely high-contrast (10^{-10} from 3 λ/D) exoplanet imaging. This level of contrast, combined with the large ATLAST aperture, is calculated to produce tens of exoEarth candidates (Stark *et alia* 2014, Ap. J., **795**, 122).

High-contrast coronagraphy requires an extremely stable telescope. Our studies indicate that picometer-level thermal stability can be achieved in a Sun-Earth L2 orbit using a JWST-like flat sunshield augmented with precision heater controls. With fewer layers of shielding, less-challenging deployment, and a constant line of sight to the sun, this sunshade will provide extraordinary thermal stability at the design temperature 273 – 293 K. It will also provide excellent stray-light suppression.

Dynamical stability can be provided using approaches such as non-contacting vibration isolation, augmented by careful structural design. Stability will be further enhanced using low-order wavefront sensing of light from the target star, perhaps augmented by high-bandwidth laser metrology-based techniques using optical controls, exploiting laser metrology-based methods.

Mirrors: The mirrors for ATLAST could be provided by multiple sources. We note in particular that lightweight Ultra-Low Expansion ULE) glass mirror segment substrates of the right size have *already* been demonstrated. Other materials and designs could also meet ATLAST specifications, leaving room for improvements in performance and cost. Studies that include testing of representative mirror segments have been proposed in response to NASA solicitations.

Serviceability: The current NASA Authorization that is in force requires all large space observatories to be serviceable, although not necessarily serviced. Our concept fulfills this requirement with externally mounted instruments and major subsystems. Not only does this offer the opportunity to upgrade instruments, but as was the case with HST, it greatly simplifies the complex integration and testing of the observatory.

Technology to enable detection of biomarkers in neighboring Earth-like worlds was identified as the highest-priority "medium activity" in the 2010 NRC Decadal Survey. Our current technology development plan has been submitted to NASA HQ to guide them in delivering on the Survey recommendations.

Instrumentation: Breakthrough potential requires breakthrough instrumentation. A notional range of options for instruments is summarized below. The high-priority enabling and enhancing (mainly detector) technologies for these instruments have been recommended for investment to NASA HQ.

Science requirements flow-down to *notional* instruments, pending engineering trade studies and further definition of the mission science goals and requirements.

Science Instrument	Parameter	Requirement	Stretch Goal
UV Imager / Multi-Object Spectrograph	Wavelength Range	100 nm – 300 nm	90 nm – 300 nm
	Field-of-View	1 – 2 arcmin	
	Resolution	< 0.20 arcsec	
	Spectral Resolution	R = 20,000 – 300,000 (selectable)	
Visible Imager / Multi-Object Spectrograph	Wavelength Range	300 nm – 950 nm	
	Field-of-View	4 – 8 arcmin	
	Image Resolution	Nyquist sampled at 500 nm	
	Spectral Resolution	R = 100 – 10,000 (selectable)	
NIR Imager / Multi-Object Spectrograph	Wavelength Range	950 nm – 1.8 μm	950 nm – 2.5 μm
	Field-of-View	3 – 4 arcmin	
	Image Resolution	Nyquist sampled at 1 μm	
	Spectral Resolution	R = 100 – 10,000 (selectable)	
MIR Imager / Spectrograph	Wavelength Range		2.5 μm – 8 μm
	Field-of-View		3 – 4 arcmin
	Image Resolution		Nyquist sampled at 3 μm
	Spectral Resolution		R = 5 – 500 (selectable)
Starlight Suppression System	Wavelength Range	400 nm – 1.0 μm	200 nm – 1.8 μm
	Raw Contrast	10^{-10}	
	Contrast Stability	10^{-11} over integration	
	Inner-working angle	36 milli-arcsec @ 1 μm	
	Outer-working angle	1.4 arcsec @ 1 μm	
Multi-Band Exoplanet Imager	Field-of-View	~1 arcsec	
	Resolution	Nyquist sampled at 500 nm	
Exoplanet Spectrograph	Field-of-View	~1 arcsec	
	Resolution	R = 70 – 500 (selectable)	

Galaxy Fueling and Quenching: A Science Case for Future UV MOS Capability

Jason Tumlinson (STScI) and David Schiminovich (Columbia)

The gas flows that drive galaxy accretion and feedback are critical, but still poorly understood, processes in their formation and evolution. One of Hubble's successes has been in characterizing the circumgalactic medium (CGM) that spans 30 times the radius and 10000 times the volume of the visible stellar disk. Thanks to Hubble and its ground-based optical collaborators, we know roughly how much matter the CGM contains, but the extremely low densities make it difficult to ascertain its exact role in galaxy evolution. The critical question is how this gas enters and leaves the galaxies: galactic star formation rates are limited by the rate at which they can acquire gas from their surroundings, and the rate at which they accumulate heavy elements is limited by how much they eject in outflows. Much of the still-unknown story of how galaxies formed comes down to how they acquire, process, and recycle their gas.

Hubble can make only crude statistical maps by sampling many halos with one absorption-line path through each. The future challenge is to "take a picture" of the CGM using wide-field UV spectroscopy that is > 50x more sensitive than Hubble. A moderate resolution (R~5000), wide-field (3-5 arcmin) multi-object UV spectrograph that can detect this CGM gas directly would revolutionize this subject. This is intrinsically a UV problem since most of the energy transferred by diffuse gas on its way in or out of galaxies is emitted or absorbed in rest-frame UV lines of H, C, O, Ne, and other metals, including rest-frame extreme-UV lines that redshift into the 1000-2000 Å band at $z > 0.5$ (Bertone et al. 2013; Fig. 1).

If sufficiently large (10-12 meters) and properly equipped, NASA's LUVOIR Surveyor will be able to map the density, temperature, and mass flow rates of the CGM, directly, using the UV radiation emitted by CGM gas as it cycles in and out of galaxies. Observing up to 50-100 sources at a time, LUVOIR could map the faint light ($S_B \sim 100$ photons cm^{-2} s^{-1} sr^{-1}) emitted by gas entering and leaving galaxies, to count up the heavy element content of this gas, to watch the flows as they are ejected and recycled, and to witness their fate when galaxies quench their star formation, all as a function of galaxy type and evolutionary state. LUVOIR could map hundreds of galaxies in fields where its deep imaging identifies filaments in the large-scale structure, and where ground-based ELTs have made deep redshift surveys to pinpoint the galactic structures and sources of metals to be seen in the CGM.

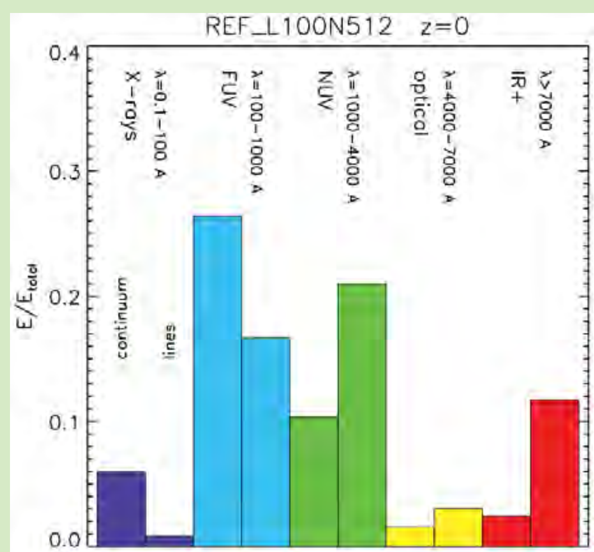


Figure 1: From "How the Diffuse Universe Cools", by Bertone, Aguirre, & Schaye (2013). The bars show the fraction of energy emitted in various rest-frame bands by gas cooling radiation in a hydrodynamical galaxy formation simulation. More than half of the radiation is emitted in the rest-frame FUV (100-1000 Å) and most of the remainder is in the NUV (1000-4000 Å).

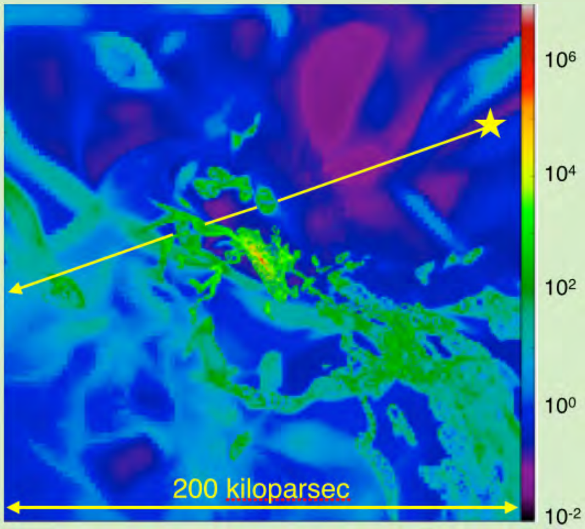


Figure 2: A visualization of the Circumgalactic Medium (CGM) gas fueling a Milky-Way like galaxy at z ~ 0.25. The color renders the strength of UV emission by C IV in the CGM gas in terms of photons cm^{-2} s^{-1} sr^{-1}. For real 2D characterization of the CGM, the LUVOIR Surveyor must reach CGM gas with $S_B \gtrsim 100$ units. The contrast between the 2D image of the CGM and the single hypothetical QSO sightline demonstrates the power of imaging the CGM over continuing to develop statistical maps from single sightlines. Image from Joung, Fernandez, Bryan, Putman and Corlies (2012, 2015).

Because this radiation is far weaker than local foreground radiation, ground-based telescopes seeking it at redshifts where it appears in the visible ($z > 2$) must perform exquisite sky foreground subtraction to reveal the faint underlying signal. These foregrounds will be considerably lower from space (by 10-100x), shortening required exposure times by an equivalent factor. Even apart from lower sky backgrounds, accessing the UV provides far better access to the relevant line diagnostics over most of cosmic time: the key lines HI Lyα, CIV 1550, and O VI 1032 are inaccessible from the ground over the last 10 billion years of cosmic time. This includes all cosmic star formation since its z ~ 2 peak, opening for view the complete co-evolution of galaxies and their gas supplies over the period when ~80% of the cosmic stellar mass density was formed (Madau & Dickinson 2015).

This unique UV capability will also address the mystery of how galaxies quench and remain so. The number density of passive galaxies has increased 10-fold over the 10 Gyr interval since $z \sim 2$ (Brammer et al. 2011). Galaxies undergoing quenching are the ideal laboratories to study the feedback that all galaxies experience: the galactic superwinds driven by supernovae and stellar radiation, the hot plasma ejected by black holes lurking in galactic centers, and the violent mergers that transform galaxy shapes while triggering the consumption or ejection of pre-existing gas. Only a 10-12 meter LUVOIR Surveyor would have the collecting area to support deep, wide-field UV MOS searches for CGM gas at the line emission fluxes that are expected, *and* the spatial resolution to observe the transformation of star forming disks to passive spheroids at 50-100 pc spatial resolution and closely examine the influence of AGN on this process. For galaxies identified as quenching, emission maps of the surrounding CGM will determine the fate of the gas that galaxies must consume or eject and powerfully elucidate the physical mechanisms that trigger and then maintain quenching. Only a 10-12 meter space telescope can achieve such spatial resolution in the optical and observe the rest-frame UV light necessary to witness the co-evolution of stars and gas in galaxies undergoing this transition. As most of the development of the present-day red sequence occurred since $z \sim 2$, and the key diagnostics are rest-frame UV lines, this critical problem is a unique and compelling driver for a 10-12 meter LUVOIR Surveyor mission in future decades.

UV/Optical/IR Surveyor: The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies

Benjamin F. Williams and Julianne J. Dalcanton
(ben@astro.washington.edu; jd@astro.washington.edu)
University of Washington

Luciana Bianchi (bianchi@pha.jhu.edu)
Johns Hopkins University

Overview: 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*. While these missions 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 in galaxies with a range of masses, metallicities, and gas content will require a large UV telescope. 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. We now discuss several science questions that should be addressed by the next large mission.

What objects produce the UV light in distant galaxies? Nearly all 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] To interpret this light 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. A Surveyor mission would, for example, allow us to characterize massive-star binaries across a wide range of environments from UV—IR SEDs. The resulting ages and mass limits will tightly constrain massive-star formation and evolution models critical to interpreting the restframe-UV of light from distant galaxies.

In addition, UV observations have 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 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.

How does feedback from star formation affect the evolution of galaxies? During their 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, as we have begun to do with *HST* in M31 and M33 (Bianchi et al., 2014; Simones et al., 2014; Williams et al., 2014). A comprehensive library of massive star UV fluxes covering as many galaxy

[1] http://www.stsci.edu/jwst/science/simulations/

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*.

What is the impact of dust on UV radiation in different environments? Only with UV observations of individual stars is it possible to separate the effects of 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). Only wide-field ($>10'$), high spatial resolution ($<0.1''$) imaging in the UV can provide the necessary data for a large enough number of stars over a sufficiently large portion of nearby galaxies to probe dust effects on the star-formation process.

What is the impact of short-lived, UV-bright stellar evolutionary stages on integrated UV-fluxes? 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. As a result, only 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*.

How do massive star clusters form? Because the UV contains a strong nitrogen-sensitive absorption feature, the UV photometry easily separates multiple stellar populations within a single cluster (e.g., Milone et al., 2012). These measurements of processes that occurred more than 12 Gyr ago are made possible by high spatial resolution, high sensitivity UV observations. 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: 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. Cameras with more than $100\times$ the current number of UVIS pixels are under construction (Gilmore et al., 2012), suggesting 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 an two orders of magnitude.

Finally, covering full stellar SEDs from the extinction bump at 2000 $\AA$ to the near-IR is ideal for separating the effects of temperature and dust. However, we note that the UV provides the most leverage at high temperatures and cannot be observed from the ground, making it the highest priority.

Bianchi, L. et al. 2012, AJ, 143, 74
Bianchi, L., & Efremova, B. V. 2006, AJ, 132, 378
Bianchi, L. et al. 2014, Advances in Space Research, 53, 928
—. 2011, Ap&SS, 335, 249
Bouwens, R. J. et al. 2010, ApJL, 709, L133
Brown, T. M. et al. 2000, ApJ, 532, 308
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Busso, G. et al. 2005, ApJL, 633, L29
Coe, D. et al. 2006, AJ, 132, 926
Engelbracht, C. W. et al. 1998, ApJ, 505, 639
Gilmore, D. K. et al. 2012, in AAS, Vol. 219, AAS, 156.04
Milone, A. P. et al. 2012, ApJ, 744, 58
O'Connell, R. W. 1999, ARAA, 37, 603
Reddy, N. A. et al. 2008, ApJS, 175, 48
Romaniello, M. et al. 2002, AJ, 123, 915
Rosenfield, P. et al. 2012, ApJ, 755, 131
Simones, J. E. et al. 2014, ApJ, 788, 12
Telesco, C. M. 1988, ARAA, 26, 343
Williams, B. F. et al. 2014, ApJS, 215, 9