COPAG Response to the Probe-class Mission Charge

Paul Scowen (ASU, COPAG Chair), Matt Greenhouse (NASA-GSFC), Joe Lazio (NASA-JPL)

1. Introduction

In January 2016, the Astrophysics Division Director, Dr. Paul Hertz, charged the Program Analysis Groups (PAGs) with a question concerning how to solicit input from the community on medium-sized mission concepts, or so-called Probe-class missions. Two options were given:

1. Issue a solicitation through ROSES for funded Astrophysics Probe mission concept study proposals. The Astrophysics Division (APD) would select a few (~10) for one-year studies with a modest (~$100K) amount of funding to be allocated for each study. The results of these studies would be presented to the Decadal Survey Committee with the option of having NASA conduct further one-year studies at a higher level of detail (and cost) for each study for a small number (~3) of concepts.
2. Do nothing and let the community self-organize. This would likely result in the submission of many white papers to the 2020 Decadal Survey from interested individuals and groups.

2. Solicitation of Input and Community Engagement

In anticipation of this move, and directly stemming from discussions held during 2015 concerning the issue of Flagship mission definition and interest, the Cosmic Origins Program Analysis Group (COPAG) solicited in December 2015 broad community input on possible Probe-class mission concepts in an open and inclusive manner via a call for two-page community white papers, the call is included as **Appendix A**. A total of 16 white papers were received. All submitted responses were considered and analyzed by a subset of the COPAG Executive Committee (EC) as part of a working group formed between the three PAGs, and are reflected in **Appendix B**. The papers themselves are included with this report as **Appendix C**. The purpose of this call and the subsequent analysis is to demonstrate the interest and need on the part of the Cosmic Origins community for a mission class that fills the void between the MIDEX mission class and the Flagship mission class.

3. COPAG Analysis and Findings

The number and breadth of the responses indicates to the COPAG that the community strongly supports the idea of a Probe-class mission opportunity. The range of science proposed, and detailed in **Appendix B** in summary form, lays out capabilities that span from the radio and FIR at the long wavelength end, through the NIR, visible and UV bands, to the X- and gamma-rays. The science itself covers cosmic history from the Dark ages, through epoch of re-ionization and the peak in star formation and black hole growth of galaxies. The science also focuses on the evolution of individual galaxies, their stellar and planetary populations, factors that affect that formation, and the cycles of energy and material that feed between the phases of the interstellar and intergalactic medium and that promote and arrest star formation under a range of conditions. All these goals, and many more, are represented by the science the Cosmic Origins community wishes to pursue with this class of mission, and to fulfill the science goals laid out in NASA roadmap documents for the current and future decades. There is also a clear overlap with the range of science proposed with the interests of both the PhysPAG and the ExoPAG, which reflects a common set of interests and goals within this mission class. Such a mission class can be seen as enabling Cosmic Origins science in a way that allows surveys and combinations of capabilities not already provided by existing facilities in the NASA portfolio.

From a technology and instrumentation perspective the mission concepts include spectrometers, cameras and photon detectors that operate either at very high energies or very long wavelengths.

The enabling technologies called out range from large format arrays at a variety of wavelengths, signal processing advances, modular mirror technologies, inflatable reflectors and improvements in optical coatings. Many concepts seek to leverage existing investments in detectors and coatings to provide a low cost, low risk solution, while others wish to take promising emerging technologies to their next logical level and open new regimes of research.

Mission lifetimes range from a few years to as many as five. Mission costs range from just above the MIDEX cutoff in some cases to around the $1B level in many cases, to a few that stray above that number mostly providing multiple instrument suites, or larger apertures than average. Cost estimating methods include conventional Team-X or IDC estimates extrapolated to current day, or similar estimates made as part of the last Decadal exercise, or by analogy with missions either under development, construction or that have flown.

In light of these examples, all submitted in good faith by our community, we believe there are ample ideas and innovation to take advantage of such a mission size opportunity. In addition, the range of information and the disparate payload sizes, passbands, instrumentation and TRL indicate that funded concept studies of the kind proposed under Option #1 from the original Charge is the most appropriate method to assemble a clearer picture of the kinds of science and technology a Probe-class mission could enable. We seek to provide to the Survey a more insightful analysis by the APD to help shape and inform the deliberations of the Survey.

Our findings are therefore:

- The COPAG finds that **there exists a wide range of community science goals** that are both consistent with current National Academy priorities and **that can be enabled with medium-class missions**.
- In light of this fact, the **Cosmic Origins community is in fact interested in supporting a line of probe-class missions** using the alternatives presented by APD in the Charge to the PAGs.
- The COPAG finds that the work of preparing high quality white paper proposals to the 2020 Decadal Survey, for missions of this class, **cannot be performed absent funding**.
- The COPAG finds that the science community prefers **a free and open solicitation process (such as a ROSES NRA) for provision of funding** to enable the above work.
- **Option #1 in the original Charge to the PAGs is therefore the preferred method** for soliciting input on such a mission size to the 2020 Decadal Survey
- **Option #2 attracted only modest levels of support**

4. Community Concerns

One community concern with the proposed AO-selected probe-class mission program was revealed during our work. The analogous Planetary Division Discovery Program AOs are restricted to a limited set of mission concepts. Whether or how such a limit would be placed on the competitive playing field in the Astronomy Division's proposed program is unclear and of great interest to the community. Hence, we recommend that the Astronomy Division invite PAG comment on this and other aspects of their draft proposal to the Decadal Survey for creation of this program.

The COPAG is concerned that the Astrophysics Division carefully consider the amount of support that would be provided by NRA awards for mission studies of this class, both in terms of funding and provision of in-kind design lab and other engineering services.

Many members of the community were concerned that Option #2 would result in varied quality of input to the Decadal Survey and would convey an apparent lack of readiness for Probe-class missions and no clear resulting recommendation – it is also recognized that Option #2 will likely happen anyhow as part of the Decadal Survey soliciting ideas from the community.

Appendix A – COPAG Call for White Papers

Cosmic Origins Program Analysis Group Call for White Papers : Probe-Class Astrophysics Mission Concepts

To: The Astronomical Community
From: The Cosmic Origins (COR) Program Analysis Group Executive Committee
Due Date: February 15, 2016
Submission: Submit PDF white papers to COPAG_Contact@bigbang.gsfc.nasa.gov

Dear Colleague,

In 2015, Paul Hertz (Director, NASA Astrophysics Division) issued a memo to the astronomical community to stimulate planning for the 2020 Decadal Survey. As part of the subsequent considerations by the COPAG and other groups, the issue of smaller Probe-class missions came up time and time again. Now that the question of Flagship mission studies is advancing to the STDT phase, it is an appropriate time for the COPAG to consider the question of Probe-class missions in a more formal fashion.

In this regard, we consider a Probe-class mission to fit within the **cost envelope between** a Mid-sized Explorer (MIDEX) mission and a Flagship. While previous considerations have used $1B as a rigid cap, we would like to see where the balance between cost and return naturally falls and consider the size of a potential mission class cost cap in that light. Experience does indicate that this kind of mission class is likely to be **meter-class in size**, but some mission designs may be unique in their formulation. Also be advised that a Probe-class mission is regarded as having a **primary mission goal of addressing a focused science investigation with a PI**, and is not intended to be a general-user type observatory, but some provision for an extended mission guest-observer program could be made if appropriate. This activity is intended to explore the COR community's interest in a line of competed PI missions, in this approximate cost range.

The Cosmic Origins Program Analysis Group (COPAG) invites you to **provide feedback** on what compelling Probe-class missions you would intend to propose to NASA using **one-to-two page white papers**. However, the papers submitted will be **made public**, so do not include proprietary information in your submissions. Please include in your submission an **initial estimate at the cost of your mission** and the basis upon which this cost estimate has been made. It should be noted that the mission cost can float above $1B but not by a lot – we are **not** soliciting mission ideas that are likely to lie in the $2-3B range and higher **– a small amount over $1B is allowable if justified**. Please also include an idea of **how long** your mission would likely take to answer its primary science goal, and what the ultimate **mission lifetime** would be. This initial call for white papers is only a start - the white papers will form a core set of community input for discussion regarding whether the establishment of a formal Probe-class mission line is warranted.

All white papers must include a title, author names, and email address of the lead author. Length is limited to 2 pages, including figures. Font size must be 10 point or greater. PDF submissions are preferred, although Microsoft Word submissions and plain text submissions are also acceptable. We recommend that you consider the following types of information below in your white paper responses. While a **deadline of February 15, 2016** is assigned, if you would like to give a **5-minute summary** presentation of your idea at the upcoming COPAG session at the **AAS meeting in Florida**, the afternoon of Monday

January 4, 2016, please let us know. If interested please send a note to the above-listed email address by **December 21, 2015**, and the presentation itself to the same address by **December 30, 2015**.

1. SCIENCE DRIVERS

Describe an important Cosmic Origins science question(s) that you think should be addressed by a Probe-class mission. Please be as specific as possible by describing science questions or specific measurements to be addressed rather than general capabilities or science areas. For example, "Do molecular clouds subjected to extreme environments (turbulence, strong tidal fields, shocks) favor high-mass star formation?" would be more useful than "observing star forming regions at unprecedented angular and spectral resolution" or "investigating high-mass star formation processes". If the particular science topic is not specifically related to Cosmic Origins, we will make sure that one of the other PAGs (PhysPAG, ExoPAG) receives your input for consideration as well. Please also be advised that the science case should be one that cannot be done with existing or currently planned facilities, such as HST.

2. TECHNICAL CAPABILITIES

Describe the performance capabilities that this mission would require to address key science questions. Include the following information (as appropriate):

- Spectral coverage, e.g. far-UV, UV/visual, near-IR to mid-IR, far-IR?
- Spectral resolving power (both for imaging and spectroscopy)?
- Angular resolution?
- Field of view?
- Primary operational mode, e.g. survey, point-and-stare, etc.?
- Sensitivity? (If you can't answer in a quantitative way, try to describe in terms of the class of object that you would want to be able to detect out to a particular distance, at a desired signal-to-noise ratio, etc.).
- Other important capabilities, e.g. multi-object slit spectroscopy, high-contrast coronagraphy, time-resolved photon-counting, etc.

3. NEW TECHNOLOGIES

Would new technologies be required by the Probe-class mission you describe above? If so, what new technologies would be required, and what is their current level of maturity (for example, "still in concept formulation", "separate components in test-bed research phase", "an integrated breadboard model has been lab-tested", "a prototype is ready for testing in an operational environment"). Specifying in terms of Technological Readiness Level (TRL) is okay too.

4. PROBE-CLASS MISSION NEEDED?

Could the science question(s) described above be addressed (in total or in part) by a smaller mission (Explorer-class, suborbital payloads, etc), or a larger flagship mission, or are the science objectives clearly in the realm of a Probe-class mission? Please make this clear.

Appendix B – Submitted White Papers Summary

Paper PI	Title	Science Topics	Passband	Wavelength / Freq.	Aperture	Instrument	Spectral Res.	Angular Res.	Field of View	Sensitivity	N(pixels)	T(Tel)	T(Instr.)	Orbit	Mass	LV	Cost	Basis	Technology
C.M. Bradford (JPL/Caltech)	A Probe-Class Opportunity for Far-IR Space Astrophysics		FIR	50-500 microns	2.5m	Spectrometer	R~500	N/A	N/A	4×10−10 W Hz−1/2	20,000	4K	50-100 mK	S-E L2	3000 Kg	Falcon-9	~$1B FY08	Flagship Costing	moderate resolution grating-type dispersive spectrometers
		Directly chart the history of cosmic star formation, supermassive black hole growth, and baryons in the cosmic web by studying gas-phase cooling lines through the epochs of peak stellar and black-hole mass growth.																	
		Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence.																	
		Measure clustering and total emission of faint galaxies below the individual detection threshold using tomo- graphic intensity mapping of the far-IR emission lines, particularly for the faint Epoch of Reionization galaxy populations.																	
		Probe the cycling of matter and energy in the Milky Way and nearby galaxies with sensitive spectral probes of the energetics of the atomic and molecular ISM.																	
J. Lazio (JPL)	PROBING THE DARK AGES AND COSMIC DAWN WITH NEUTRAL HYDROGEN		Radio	15-120 MHz	"small"	Spectrometer	0.5/0.1 MHz	5 deg/3'	2*pi Sr/10 sq deg	3/1 mK	N/A	Ambient	Ambient	Far side of the Moon	1000 Kg	N/A	<$1B	PSD analog	Detector and Signal Processing in the Radio
		Dark Ages (*z* > 35): Before the first stars formed, the gas is expected to have cooled rapidly relative to the CMB, causing the H I feature to appear in absorption.																	
		First Stars (35 > *z* > 20): After the first stars appeared, their UV radiation couples to the H I line through the Wouthuysen-Field effect.																	
		First Accreting Black Holes (20 > *z* > 15): Hot accretion disks around the first stellar remnants (e.g., black holes) emit X-rays, which efficiently heat the cold H I gas.																	
		Epoch of Reionization (15 > *z* > 6): Eventually, UV photons from stars and black holes started ionizing the gas in giant bubbles within the IGM.																	
M. Ulmer (Northwestern)	An orbiting wide-field x-ray imaging spectrometer (WFXIS)		X-ray	0.1-2.5 keV	N/A	Spectrometer	5eV	10'	80+ degrees	N/A	500x500	Ambient	Ambient	N/A	N/A	N/A	N/A	N/A	large format x-ray arrays
		clusters of galaxies, from those with sub-clumps to those at the edge of the universe																	
		individual galaxies																	
		deep sky surveys for clusters and QSO/AGN,																	
		supernova remnants (SNRs) in galaxies such as the LMC, SMC and Andromeda																	
		knots in galactic SNRs such as Cas-A																	
		the large scale structure of the ISM, nearby clusters of galaxies, and large SNRs, such as the Cygnus loop and the Vela/Puppis region.																	
M. Ulmer (Northwestern)	An all-sky low-energy gamma-ray observatory (ALLEGRO)		Gamma ray	7-200 keV	2000 cm^2 eff.	Spectrometer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Advances in electronics, computing power, and data storage and retrieval with high time resolution
		the understanding of gamma-ray bursts																	
		rotationally powered neutron stars																	
		binary x-ray sources																	
		monitor the hard x-ray sky, provide hard x-ray maps, and even provide a stringent test of the general relativistic Shapiro delay.																	
P. Roming (SWRI)	Death of Massive Stars (DoMaS) Probe		Soft X-ray/NIR/FUV	0.2-5keV / 0.7-2.5micron / 130-300nm	1m/1m/0.5m	Camera+spectrographs	R=40/1000/1000	1'/1"/1"	2.4Sr/30'/30'	1.6 x 10-11 erg cm-2 s-1 3.9x10-20 ergcm-2 s-1 Å-1 @1.6μm in 1s 2.4x10-17 ergcm-2 s-1 Å-1 @1700Å in 1s	N/A	N/A	N/A	GEO	N/A	N/A	$762M FY16	NICM	GaN MCP - all other @ TRL 6 already
		Nature of the First Stars and Their Contribution to Reionization																	

Paper PI	Title	Science Topics	Passband	Wavelength / Freq.	Aperture	Instrument	Spectral Res.	Angular Res.	Field of View	Sensitivity	N(pixels)	T(Tel)	T(Instr.)	Orbit	Mass	LV	Cost	Basis	Technology
	Nature and Death of Massive Star Progenitors																		
	Ancillary Targets - lower redshift sub-luminous, short, and long GRBs; thermonuclear bursts; flare stars; SNe Ia breakouts; superfast X-ray transients; classical no- vae; tidal disruption events; blazars; AGNs; soft γ-ray re- peater flares; and hot OB stars with winds																		
H.A. MacEwen (Reviresco LLC)	FORERUNNER for the EVOLVABLE SPACE TELESCOPE (ForEST)		UV-Vis-IR	N/A	4m	Mirror deployment	N/A	N/A	N/A	N/A	N/A	Ambient	Ambient	cislunar	5000 Kg	N/A	N/A	N/A	Modularized mirror deployment with a view to 10m+ telescopes in the future
	Pure Technology Paper																		
P.A. Scowen (ASU)	HORUS – THE HIGH ORBIT ULTRAVIOLET-VISIBLE SATELLITE		NUV-Visible / FUV	200-1075nm / 100-170nm	2.4m	Camera / Spectrograph	R=40,000	0.05"	14'	1 x 10-16 erg cm-2 s-1	64,000	Ambient	Ambient	ES-L2	N/A	Delta-IV	$1.28B FY17	Decadal 2010 study extrapolated	Large focal plane arrays, dichroics, MCPs - all TRL 5 or higher
	an imaging census of all high-mass star formation sites within 2.5 kpc of the Sun to determine how frequently solar systems form and survive																		
	Survey all major star forming regions in the Magellanic Clouds to sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies.																		
	Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed.																		
	Measure star formation and metal production rates in the distant universe to determine how galaxies assemble																		
F.R. Hearty (Penn State U.)	Deep Survey Telescope: Exploring the First Billion Years		NIR/MIR	0.5-5 microns	4m	Camera	16 filter bands	0.2"/pixel	1.6 degrees	~27mag in 60 s	829 Gpix	70 K	70K	N/A	N/A	N/A	requires "breaking" of cost curve to fit inside $1B	N/A	Same as WFIRST-AFTA with emerging tech for other aspects
	How was large-scale baryonic structure assembled in the early Universe? DST will identify at high redshift: the first QSOs, the earliest massive galaxies and galaxy clusters, high redshift supernovae of all varieties																		
	DST will identify at low redshift: Host galaxy type and redshift for each supernova discovered by LSST, progenitor star for many future supernovae from Local Group to Virgo cluster, Tidal streams and halo structures for Local Group galaxies																		
	DST will identify in our Solar System: potentially hazardous asteroids, near-Earth asteroids down to 30m, planet (and dwarf planet) resident in Kuiper Belt, Inner Oort Cloud, and possibly Oort Cloud itself																		
S. Rinehart (GSFC)	The Space High-Angular Resolution Probe for the InfraRed (SHARP-IR)		FIR	20-160 microns	12m baseline	Interferometer	N/A	0.3-2.75"	N/A	N/A	N/A	Ambient	4K	N/A	N/A	N/A	>MIDEX	SPIRIT & FKSI experience	Detector development needed - all else already proven
	to observe crucial atoms, ions, and molecules such as water as well as continuum sources																		
	to enable discoveries in the areas of star and planet formation, AGN, obscured star forming galaxies at high redshifts, cool objects in general, and the outer solar system																		
P.A. Scowen (ASU)	ORION UV-VISIBLE PROBE		NUV-Visible	200-1100nm	1.2m	Camera	12 filter channels	0.1"/pixel	14'	1 x 10-16 erg cm-2 s-1	64,000	Ambient	Ambient	ES-L2	N/A	N/A	$358M FY17	Two Team-X studies	Large focal plane, technologies TRL 5 or higher
	an imaging census of all high-mass star formation sites within 2.5 kpc of the Sun to determine how frequently solar systems form and survive																		
	Survey all major star forming regions in the Magellanic Clouds to sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies.																		
	Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed.																		
A. Cooray (UC Irvine)	Cosmic Dawn Intensity Mapper		IR	0.7-7 microns	1.5m	Spectroscopic Imager	R=200-300	1"/pixel	10 sq deg	1 x 10-18 erg cm-2 s-1	129 Gpix	N/A	N/A	N/A	N/A	N/A	$850M	ESA M5 proposal	HgCdTe detectors & linear variable filters
	pioneering observations of the Lyman-α, Hα and other spectral lines of interest throughout the cosmic history, but especially from the first generation of distant, faint galaxies																		
	produce a three- dimensional tomographic view of the epoch of reionization (EoR), mapping Lyα emission from galaxies and the intergalactic medium (IGM)																		
	map out, for example, Hα emission from z=0.2 to reionization, providing a three-dimensional view of the star-formation history, its environmental dependence, and clustering over 90% of the age of the Universe																		

Paper PI	Title	Science Topics	Passband	Wavelength / Freq.	Aperture	Instrument	Spectral Res.	Angular Res.	Field of View	Sensitivity	N(pixels)	T(Tel)	T(Instr.)	Orbit	Mass	LV	Cost	Basis	Technology
S. Heap (Eureka Scientific)	Galaxy Evolution Spectroscopic Probe (GESP)		NUV / NIR	200-400nm / 800-1600nm	1.5m	MOS	R~500	Adjustable slits	0.03-0.08 sq deg	2x10-18 ergcm-2 s-1 Å-1	243 slits	Ambient	Ambient	N/A	N/A	N/A	<$1B	"design to cost" approach	slit generator, convex grating
		GESP will study the physics of the ISM, accretion and star formation, stellar feedback, and galactic winds																	
		GESP will answer: what are the roles of stellar feedback, AGN feedback, and dark energy in driving galaxy evolution																	
M. Robberto (STScI)	A Near-IR All-Sky Spectroscopic Probe		NIR	0.8-1.8 microns	1.5m	Slit selector + spectrograph	R~400	0.75" slits	0.4 sq deg	AB~23 mag in 15 mins	N/A	Ambient	Ambient	N/A	N/A	N/A	<$1B	previous ESA small mission proposal	DMD @ TRL 6
		to perform the most accurate measurement of the expansion history of the Universe (using baryonic acoustic oscillations) and the growth history of cosmic large scale structure (using redshift space distortions), measuring the redshifts of ~500 million galaxies regardless on their spectral type and environment																	
		to understand galaxy build-up and evolution by analyzing the detailed information contained in the same spectra																	
C.K. Walker (U. Arizona)	Terahertz Space Telescope		THz	30-300 microns	20m inflated	Coherent cameras	R~10^3-10^6	0.4-4"	N/A	~1x10-18watt/Hz1/2	N/A	Ambient	4-6K	N/A	600 Kg	N/A	<$750M	unclear	inflatable spherical reflector, THz detectors
		Star formation through cosmic time																	
		• Galaxy formation and evolution: from quasars, Seyferts, and starbursts to the Milky Way																	
		• Life cycle of the interstellar medium																	
		• Galactic ecology																	
		• Astrochemistry																	
		• Formation of solar systems: debris disks, protoplanetary evolution, Kuiper Belt objects, asteroids and comets, planetary atmospheres																	
M. Ulmer (Northwestern)	The Next Generation Space UV-Vis Space Observatory (NG-SUVO)		UV-Visible	350-10000nm	2.4m	Camera	Filters	0.03"	6'	unclear	N/A	Ambient	Ambient	N/A	N/A	N/A	$2B FY17	Descope of 2009 paper estimate	improvements in optics (coatings) and detectors
		1. A study of the hot intracluster medium of rich clusters of galaxies																	
		2. He II absorption and the ionization history of the Universe out to z of 4.																	
		3. Observing metals in intergalactic filaments																	
		4. Observing the warm hot intergalactic medium (WHIM) and the relationship between galactic winds and metal enrichment of the WHIM.																	
		5. Detecting metals in planetary disks leading toward an understanding the relationship between the metallicity in proto-planetary disks and planet formation.																	
		6. Detecting the water absorption and perhaps even DNA-protein-like absorption features in the atmospheres of extra-solar planets (or extra-solar moons such as Europa or Enceladus).																	
		7. Imaging aurorae on solar system planets, e.g. Jupiter																	
P. Goldsmith (JPL)	SPECtroscopic TeRAhertz Satellite “SPECTRAS”		THz	300-5000 GHz	6m	Spectroscope	low-res	4-25"	256-1600"	4x better than Herschel	5x64	5-10K	4K	ES-L2	<7000 Kg	Falcon9H	$1.4B	Team X	THz detectors derived from Herschel
		will target the most important low-lying transitions of both HDO and other isotopologues of water, enabling accurate measurements of the D/H and oxygen isotopic ratios in a large number (on the order of 20) of comets																	
		water will be a uniquely powerful tracer of the collapse of dense star-forming cores																	
		SPECTRAS’s higher sensitivity it will possible to survey many nearby disks and determine their gas-phase water content																	
		Atomic fine structure lines are valuable probes of the interstellar medium and star formation																	

Appendix C – Submitted White Papers

A Probe-Class Opportunity for Far-IR Space Astrophysics

C.M. Bradford (JPL/Caltech)[1], J. Aguirre (U. Penn), P. Appleton (Caltech), L. Armus (Caltech), J. Bartlett (JPL), A.D Bolatto (Maryland), A. Cooray (UC Irvine), D. Dale (U. Wyoming), O. Dore (JPL/Caltech), P.F. Goldsmith (JPL), C. Lawrence (JPL), J.D. Smith (U. Toledo), J. Vieira (U. Illinois), H. Yorke (JPL), J. Zmuidzinas (Caltech/JPL)

February 15, 2016

1 Motivation

The far-IR waveband (broadly 30–1000 μm) accesses a rich and wide-ranging scientific landscape, yet remains a technical frontier for which rapid scientific advances are still possible at sub-flagship cost. While there is great astrophysical promise, the world has not yet brought together the two key elements required for sensitive far-IR measurements: an actively-cooled space telescope operating near the temperature of the microwave background (e.g.$\sim$4 K), and sensitive, large-format far-IR detector arrays. NASA is now poised to integrate these building on system-level experience with Spitzer, Herschel, and Planck, and augmented with detector development progress and new low-cost telescope technology. This possibility has produced great excitement in the far-IR community, as evidenced with our well-attended workshop in June 2015 focusing on a flagship-class 'Far-IR Surveyor.'[2]

Here we emphasize that because the far-IR is so fertile and as yet relatively unexplored, large advances are possible with a mission that is smaller in scope than the d$\geq$5-meter Surveyor under consideration for the Decadal. The far-IR is particularly compelling for sensitive wideband spectroscopy, which overcomes source confusion and provides redshifts and unique astrophysical diagnostics of the inner workings of dusty galaxies and star- and planet-forming sites. While the probe outlined below will not offer the ultimate point-source sensitivity or speed of the Surveyor (required for individual early-Universe objects), it will nevertheless obtain spectra of thousands of objects, both targeted (e.g. JWST, WFIRST follow-up) and in blind surveys. Sources range from dusty galaxies to heavily enshrouded young stars and protoplanetary disks in our own Galaxy. Far-IR spectra will directly address several key goals of modern astrophysics:

- Directly chart the history of cosmic star formation, supermassive black hole growth, and baryons in the cosmic web by studying gas-phase cooling lines through the epochs of peak stellar and black-hole mass growth.
- Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence.
- Measure clustering and total emission of faint galaxies below the individual detection threshold using tomographic intensity mapping of the far-IR emission lines, particularly for the faint Epoch of Reionization galaxy populations.
- Probe the cycling of matter and energy in the Milky Way and nearby galaxies with sensitive spectral probes of the energetics of the atomic and molecular ISM.

We emphasize for the last two programs, surface brightness sensitivity is paramount, and is readily provided by a modest-aperture telescope.

2 A Strawman Far-IR Astrophysics Probe

In the left panel of Figure 1 we show discovery potential (plotted as survey time – lower is better) for spectroscopic measurements from space. Orders of magnitude improvement are possible relative to the Herschel instruments; much of this derives from cooling the telescope and using optimized instrumentation with background-limited detectors. Telescope area, a typical driver of mass and cost, is only one aspect of these potential gains. As a point design, we consider a 2.5-meter cryogenic telescope with moderate-resolution (R$\sim$500) wideband spectrometers covering 50–500 μm with $\sim$20,000 detectors. We also include SPICA, a 2.5-meter telescope being proposed Europe and Japan, and emphasize that even if SPICA proceeds, the probe considered here offers improved instrumentation (5–10$\times$ format increase and 2–3$\times$ per-pixel sensitivity increase) which would make it substantially more sensitive that SPICA for 3-D spectral surveys. We now consider the basic parameters of a far-IR astrophysics probe (summary in Table 1).

Mission Design. A key requirement is telescope temperature—while a non-cooled telescope may be useful for heterodyne spectroscopy, a telescope which is actively cooled to a few degrees K is vital for the broad range of far-IR astrophysics under discussion. This common requirement for all future far-IR missions drives important architecture elements, regardless of mission size. A far-IR mission requires a careful thermal design integrating passive (radiative) cooling, and active cooling provided by closed-cycle ^{4}He and ^{3}He cryocoolers such as those available from Sumitomo or US vendors. It also requires a thermally-friendly orbit such as sun-earth L2 or earth-trailing; models indicate that cryogenic systems of any size indicate are not viable in low-earth orbit. Fortunately, it seems that reaching L2 is now viable for a 2–3 ton probe with a commercial launcher (e.g. SpaceX Falcon-9).

---

[1] `bradford@caltech.edu`

[2] `https://conference.ipac.caltech.edu/firsurveyor/page/documents`

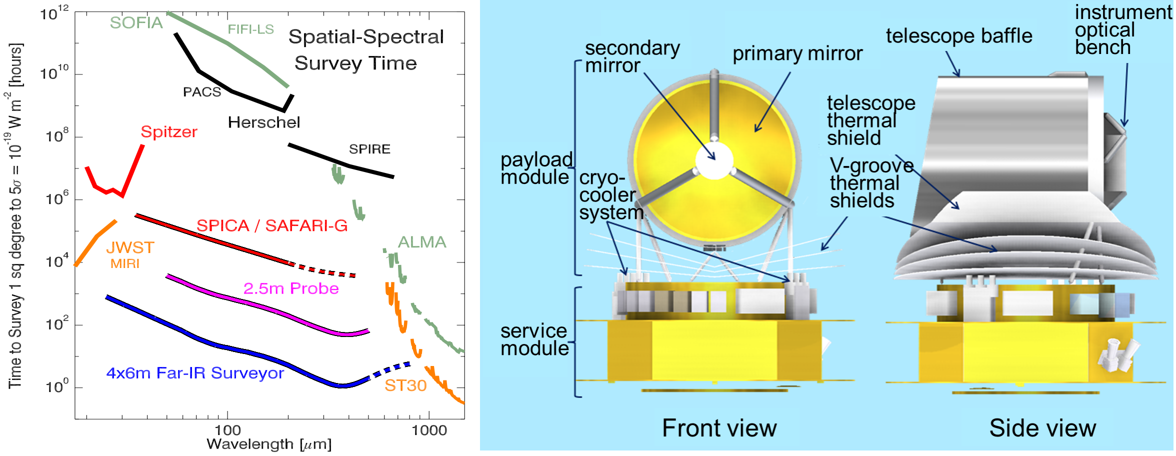


Figure 1: LEFT: Spectroscopic sensitivities plotted as spectral survey time in the far-IR and submillimeter. The Far-IR Surveyor concept has a 4×6 meter telescope, equipped with R=500 grating spectrometers with 100 beams (at each wavelength) and 1:1.5 instantaneous bandwidth. Detectors are assumed to operate with NEP = 2×10^{-20} WHz$^{-1/2}$. The SPICA / SAFARI-G curve refers to the new SPICA configuration: a 2.5-meter telescope with a suite of R=300 grating spectrometer modules with 4 spatial beams, and detectors with NEP=2×10^{-19} WHz$^{-1/2}$. Advances in instrumentation on a 2.5-meter facility could improve on SPICA substantially—the 2.5 meter probe assumes R=500 grating spectrometers with 15 beams per band, and detector NEP of 4×10^{-20} WHz$^{-1/2}$, a sensitivity demonstrated in the lab. RIGHT: Schematic of the SPICA concept: provided as one potential example of a cryogenic 2.5-meter class mission; it uses a thermal architecture similar to Planck with passive and active cooling.

Telescope. Because the telescope manufacture and iterative figuring / cryogenic testing are the dominant terms in the system cost estimates, this is a key area to address. A promising avenue of study is novel telescope techniques optimized for a cryogenic far-IR mission. For example, a low-bandwidth active system, if has sufficiently high surface control authority at sufficiently low dissipated power could allow figure adjustment on orbit. This would greatly reduce or even eliminate much of the costly cryogenic optical testing and re-figuring that is required with a traditional telescope, and likely reduce mass. Of course, for a given architecture, minimizing the aperture offers savings in figuring and testing, and also in reduction of the cold mass, which scales though the full system. In particular, a telescope such as our probe in the 2–3 meter class avoids the need for deployable structures—the full system including the sunshades and secondary mirror could fit within a 5-meter shroud, eliminating the need for costly mechanisms.

Instrumentation. The probe will have moderate resolution grating-type dispersive spectrometers: 4–5 bands can combine to cover the full decade of wavelength range. Detectors will operate near the photon background limit, with an NEP at or below 4×10^{-10} W Hz$^{-1/2}$. The baseline 20,000 pixels is conservative: frequency-domain readout techniques now being used on the ground greatly increase the format available per heat lift and per dollar, and we note that the Surveyor design includes provision in cryogenic heat loads and warm-side power for up to 500,000 pixels.

Summary, Cost. While a well-costed probe-class far-IR mission is not yet on the table, the probe outlined here is a great simplification of the 4×6-meter with deployed sunshade and secondary studied at JPL in 2008 which has evolved into the Far-IR Surveyor concept. It should therefore have a much lower cost than the Surveyor's estimated \$1.7B. We look forward to studying this, and expect that it will be within striking distance of a ∼\$1B cap. In any case, a competed opportunity would generate the most efficient solutions, and excellent science value.

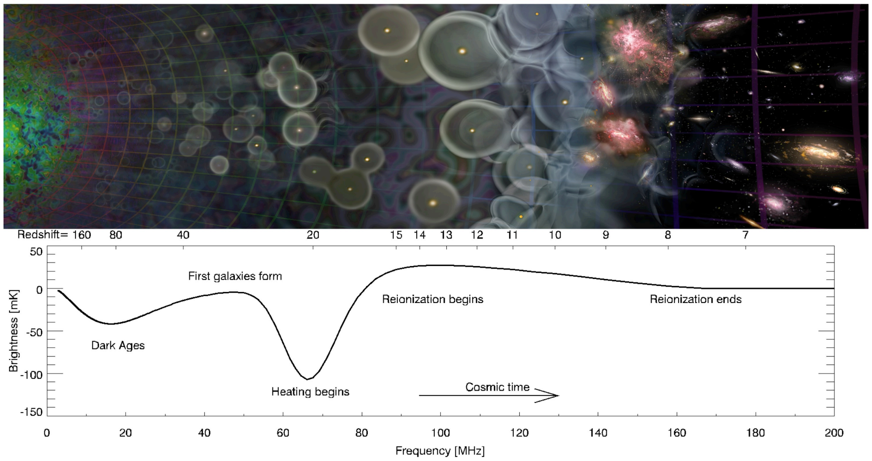
Table 1: Strawman Far-IR Probe

Parameter	Ex. FIR Probe	notes
Telescope Temperature	∼ 4 K	Key sensitivity requirement
Telescope Diameter	2–3 m	Leading term in cost
Wavelength Range	50–500 μm	Complements JWST, ALMA spectroscopic capabilities, can be optimized
Telescope Surface Accuracy	1–2 μm	Could be reduced for mission targeting the long wavelengths
Instrument Temperature	50–100 mK	Key for instrument sensitivity, common for all future far-IR missions
Total Number of Detectors	$1\text{–}5\times10^4$	Comparable to the large ground-based instruments
Heat Lift at 4 K	∼50 mW	Scaled from Planck, terms from telescope mass and sub-K mass
Heat Lift at 20 K	∼0.6 W	Scaled from Planck, terms from telescope mass and # detectors
Data Rate	∼ 100 Mbit / sec	Scales with survey ambition
Orbit	Sun-earth L2 halo	Key for thermal stability
Mass estimate	<3000 kg	Scaled from 2008 Team-X 4×6 meter study
(Falcon 9 performance to L2)	3700 kg	SpaceX via Matt Abrahamson @ JPL

PROBING THE DARK AGES AND COSMIC DAWN WITH NEUTRAL HYDROGEN[1]

J. Lazio[2], A. Loeb[3], J. Aguirre[4], J. Bowman[5], J. Burns[6], O. Doré[2], S. Furlanetto[7], C. Lonsdale[8], A. Parsons[9], J. Pober[10]

The *New Worlds, New Horizons* Decadal Survey identifies "Cosmic Dawn" as one of the three science objectives for this decade. This epoch is the final unresolved frontier of cosmology, defining a complex and rich target for observations and a research area that is likely to remain vibrant well into the next decade.



(*Top*) Schematic of the evolution of the Universe. The CMB is formed at the extreme left, and today ($z = 0$) is at the extreme right. The yellow dots with surrounding spheres represent the first stars and their Stromgren spheres. As the first galaxies form, these Stromgren spheres begin to overlap and the Universe reionizes. (*Bottom*) Illustration of the redshifted neutral hydrogen spectral feature, as a function of redshift (top axis) and frequency (bottom axis). While the exact shape of this H I spectral feature depends on the detailed evolution of the Universe, the existence of a such a signal is a robust prediction of our cosmological model; the schematic shape shown here represents one model and is likely to be relatively generic.

Following recombination ($z \approx 1100$), neutral hydrogen (H I) became the dominant baryonic component of the intergalactic medium (IGM). The highly redshifted H I hyperfine line is the *only* electromagnetic probe of the Universe before the formation of the first stars and would allow the cosmological investigation of the formation of the first gravitationally bound systems over the largest volumes of any approach. Multiple epochs accessible via the H I line can be identified (see figure), which are only poorly constrained by current observations:

Dark Ages ($z > 35$): Before the first stars formed, the gas is expected to have cooled rapidly relative to the CMB, causing the H I feature to appear in absorption. Observations of the feature at these redshifts probe the gravitational collapse of the first structures and are exquisitely sensitive to any energy injection into the IGM (e.g., decaying dark matter).

---

[1] © 2016. California Institute of Technology. Government sponsorship acknowledged.

[2] Jet Propulsion Laboratory, California Institute of Technology

[3] Harvard University

[4] University of Pennsylvania

[5] Arizona State University

[6] University of Colorado, Boulder

[7] University of California, Los Angeles

[8] Haystack Observatory, Massachusetts Institute of Technology

[9] University of California, Berkeley

[10] Brown University

First Stars ($35 > z > 20$): After the first stars appeared, their UV radiation couples to the H I line through the Wouthuysen-Field effect. This coupling creates a large absorption H I feature, which can be used to probe the spectra of the first stars, potentially distinguishing between Pop II and Pop III stars.

First Accreting Black Holes ($20 > z > 15$): Hot accretion disks around the first stellar remnants (e.g., black holes) emit X-rays, which efficiently heat the cold H I gas. Observations of the H I feature during this period are sensitive to the properties of the black holes and the metallicity of their progenitors, offering further insight into primordial star formation.

Epoch of Reionization ($15 > z > 6$): Eventually, UV photons from stars and black holes started ionizing the gas in giant bubbles within the IGM. Rapid destruction of the neutral gas then eroded the H I feature; the topology of these bubbles constrain the nature of the first galaxies, including those too faint to be detected through other means.

Tracking the evolution of the Universe during these epochs is already underway—the *Hubble* Space Telescope is providing constraints on the nature of galaxies in the Epoch of Reionization, the *Fermi* Gamma-Ray Telescope has identified gamma-ray bursts at $z > 6$, and the *James Webb Space Telescope* is likely to probe even deeper in redshift. However, a complete understanding of the evolution of the Universe over these epochs requires tracking all of its constituents, including the H I gas from which the first stars formed. Ground-based efforts to detect the H I line features are underway, but, at the highest redshifts, measurements from the ground are fundamentally limited by the ionosphere, interference, and instrument stability. The excellent characteristics of a space platform are essential to study at the highest redshifts, which are the strongest probes of cosmology and new physics.

Technical Capabilities

At these redshifts, the H I feature appears at meter wavelengths: for reference, at $z = 20$, the transition is observed at 67 MHz (λ4.5m), and, at $z = 70$, at 20 MHz (λ15m). Two measurement approaches exist. The **sky-averaged spectrum** is the most basic quantity (lower panel, figure). The different eras described above imprint distinct features on this spectrum, and its shape can be used to determine the timing of major events during the evolution of the Universe. This measurement potentially can be accomplished with a single, small antenna. The **power spectrum of H I fluctuations** allows the growth of structure to be tracked. It is therefore much more powerful than the sky-averaged spectrum, but it is also more difficult to measure because the signal from each structure is extraordinarily small. This measurement requires significant sensitivity on a range of angular scales.

The Table summarizes key technical capabilities for both measurement approaches. The challenges of obtaining sufficient sensitivity at the highest redshifts ($z > 30$) suggest that fluctuation power spectra at these redshifts are likely to be well in the future, thus the frequency range is somewhat more restricted for the power spectrum requirements. Finally, we emphasize that the values shown here are *notional* and are likely to be guided by on-going experiments and telescopes on the ground, and potentially by discoveries at other wavelengths.

	Sky-Averaged Spectrum	**H I Fluctuation Power Spectrum**
Spectral coverage	15 MHz–120 MHz	40 MHz–120 MHz
Spectral resolution	0.5 MHz	0.1 MHz
Angular resolution	≥ 5°	3 arcminute
Field of view	2π	10 deg^2
Sensitivity	3 mK	1 mK

New Technologies

Previous concept studies have identified a number of technologies that would enhance future Dark Ages-Cosmic Dawn missions (Lazio, Hewitt, et al., “The Lunar Radio Array,” Astrophysics Strategic Mission Concept Studies), and there has been an Explorer-class concept (Dark Ages Radio Explorer) developed for measuring the sky-averaged spectrum at redshifts $z \approx 20$.

The most demanding aspect of both measurement approaches is **calibration and system engineering** related to the control of systematics, rather than specific detector or signal processing technologies. The latter are both currently under development for various ground-based experiments and telescopes. For both measurement approaches, the expected signal is in the range of 10^{-4}–10^{-7} weaker than the Galactic synchrotron emission and other foregrounds. Even small changes in the performance of the instrument could obscure or vitiate the measurement.

Need for a Probe-class Mission

A measurement of the *sky-averaged* H I spectral feature at $z \approx 20$ can likely be performed with an Explorer-class mission. Fully exploiting the H I line will require obtaining higher angular resolution, probing deeper in redshift, or both. In turn, multiple antennas will be needed in order to obtain adequate sensitivity in a reasonable amount of time, sufficient angular resolution, or both. We use a previous study of an interferometric array conducted under the Lunar Sortie Science Opportunities (LSSO) program and the MoonRise mission as our "analogs."

MoonRise has been a proposed New Frontiers (Planetary Sciences) mission to study the far side of the Moon. Its total payload is of order 1000 kg, with an estimated cost of less than $1B. Therefore, we use 1000 kg as the target mass budget for a future Cosmic Dawn Probe. The LSSO concept study considered an array of tens of antennas (~ 50), for which the mass budget was approximately 500 kg. While further study is required, the combination of MoonRise and the LSSO concepts indicate that a Cosmic Dawn Probe, consisting of tens of antennas could be implemented within the current specifications for Probe-class missions.

Title: Concept for an orbiting wide-field x-ray imaging spectrometer (WFXIS)
Authors: Ulmer, Melville P.

We present a concept study for a mission to provide wide field x-ray imaging spectroscopy. Many astrophysical studies in the x ray regime demand both high energy resolution (approximately 5 eV) as well as high angular resolution (approximately 10'). Examples of such studies are: clusters of galaxies, from those with sub-clumps to those at the edge of the universe (minimum radii approximately 15'); individual galaxies (nearby ones are easily resolvable on the 10' scale); deep sky surveys for clusters and QSO/AGN, which necessitate optimal sky coverage with the avoidance of source confusion for long exposures (approximately 2 multiplied by 10^5 sec); supernova remnants (SNRs) in galaxies such as the LMC, SMC and Andromeda; knots in galactic SNRs such as Cas-A; and fine structure in the interstellar medium (ISM). Other studies that require a wide FOV and high energy resolution are studies of the large scale structure of the ISM, nearby clusters of galaxies, and large SNRs, such as the Cygnus loop and the Vela/Puppis region. The instrument concept we propose, the Wide Field X-ray Imaging Spectrometer (WFXIS), will combine the critical characteristics of wide-field, high-resolution x-ray imaging with high energy resolution, and thus provide unique capabilities not available on any single current or planned mission in which NASA is participating. Our preliminary design consists of ROSAT-sized zerodur mirrors with a Ritchey-Chretien figure; approximately 2.5 meter foal length; and a single focal plane detector made up of a 500 multiplied by 500 pixel array of either microcalorimeters or superconducting tunnel junctions. The energy range covered by this system will be approximately 0.1 - 2.5 keV. The main points of this work are: the science is outstanding; the technology for mirror production and design is in hand; and detector technology has reached the stage that it makes sense to begin planning for the ability to make 500 multiplied by 500 pixel arrays with a factor of 10 improvement in energy resolution over available CCDs.

Full paper found at http://adsabs.harvard.edu/abs/1995SPIE.2515..280U

Title: Concept for an all-sky low-energy gamma-ray observatory (ALLEGRO)

Authors: Ulmer, Melville P.; Purcell, William R.; Matz, S. M.; Finley, J. P.; Cordes, James M.; Wilson, Robert B.

We describe a concept for a NASA mission to study gamma-ray bursts, pulsars, and hard x- ray transients. That a large area all sky monitor is an outstanding design was demonstrated by the BATSE (Burst And Transient Source Experiment) on board the Compton Gamma-Ray Observatory (CGRO). The proposed All Sky Low Energy Gamma-Ray Observatory (ALLEGRO) will combine the best characteristics of BATSE and OSSE (Oriented Scintillation Spectrometer Experiment), namely continuous all-sky coverage with a reduced background obtained from relatively narrow field of view collimation. The design goals call for an effective area of greater than or approximately equal to 2000 cm^2 (in the 20- 200 keV range) provided by 35 separate detectors aligned to cover the entire sky, plus 1/8 ms time tagging of all events and energy coverage from 7 - 200 keV. We combine this with what have probably been the greatest advances in technology over the past few years, namely, advances in electronics, computing power, and data storage and retrieval. With these capabilities plus enhancements to the design based on our experience with BATSE and OSSE, we will explore the realm of high time resolution phase space with all-sky coverage at unprecedented sensitivity. Such a satellite will provide a myriad of fascinating studies of the hard x-ray sky. Three general areas where we expect to make major advances are the understanding of gamma-ray bursts, rotationally powered neutron stars, and binary x-ray sources. As an added bonus, this satellite will allow us to monitor the hard x-ray sky, provide hard x-ray maps, and even provide a stringent test of the general relativistic Shapiro delay.

Link to full paper:
http://adsabs.harvard.edu/abs/1995SPIE.2515..544U

Death of Massive Stars (DoMaS) Probe

Pete Roming[*] (proming@swri.edu), Eric Schlegel[†], Thomas Greathouse[*], Neil Gehrels[*],
Chris Fryer[+], Derek Fox[◆], Michael Davis[*], Amanda Bayless[*]

I. INTRODUCTION

The death of massive stars is a fundamental process in the shaping of the Universe. The first massive stars are considered a significant contributor to reionization and the dispersal of the first metals. These first stars also form the seeds for the formation of supermassive black holes (e.g. 1-2). Later generations continue the production and dissemination of heavy elements, which shape planets, solar systems, future generation of stars, and galaxies. They form the neutron stars and black holes in the universe, dictating the characteristics and formation rates of X-ray binaries, X-ray bursts and gravitational wave sources (e.g. 3-5). Despite their importance, the nature of the first stars, when and how they reionized the Universe, and how massive stars end their lives, is not well understood. An astrophysics probe-class mission with greatly expanded capabilities, such as DoMaS, will readily address these problems.

II. SCIENCE DRIVERS

Massive stars end their lives as gamma-ray bursts (GRBs) and supernovae (SNe). Because of their extreme luminosities, GRBs are excellent probes for addressing the nature of the first stars and when and how they contributed to reionization, while the shock breakout (SBO) of SNe is one the best tools for ascertaining the nature and death of massive star progenitors.

2.1. Nature of the First Stars and Their Contribution to Reionization

The first stars are arguably massive (e.g. 6) and some will end their lives as GRBs (e.g. 7). Sufficiently high signal-to-noise (S/N) spectra of the corresponding afterglows will deliver measurements of the HI fraction in the IGM at the redshift of the bursts (i.e. 8). These afterglows will be exceptionally valuable targets for such studies, as they have featureless, synchrotron power-law spectra, permitting straightforward identification of the absorption signatures, thus uncovering the metallicity and ionization states in their host galaxy. These spectra will reveal the history of reionization, including variations along multiple sight lines; the escape fraction of ionizing radiation from high-z star forming regions, an important variable in reionization models; and the processes of metal enrichment in the early Universe.

2.2. Nature and Death of Massive Star Progenitors

The first electromagnetic signature in the death of massive stars is the SN SBO, which is strongly manifested in the soft X-ray and EUV regimes (e.g. 9-10; Fig. 1). High S/N spectra within seconds to minutes after the SBO event will uncover the true nature of the physics behind these events, an area that is still poorly understood. The properties of the SBO – such as temperature, energy, and photon diffusion time (11) – provide a powerful way of exploring the photosphere of the star and constraining the SN progenitor. These spectra are superb probes of: stellar radii, which are key in eliminating major uncertainties in binary population synthesis models (e.g. distinguishing between compact mergers being black holes and double neutron star systems - important for LIGO); stellar mass-loss that reveal the quantity of mass lost for different stars, ultimately determining the remnant mass distribution; and stellar mixing, crucial for removing major uncertainty in stellar evolution and SNe, including nucleosynthesis and galactic chemical evolution. Detection of SBOs also provides an alert to observers of a new SN immediately after core collapse.

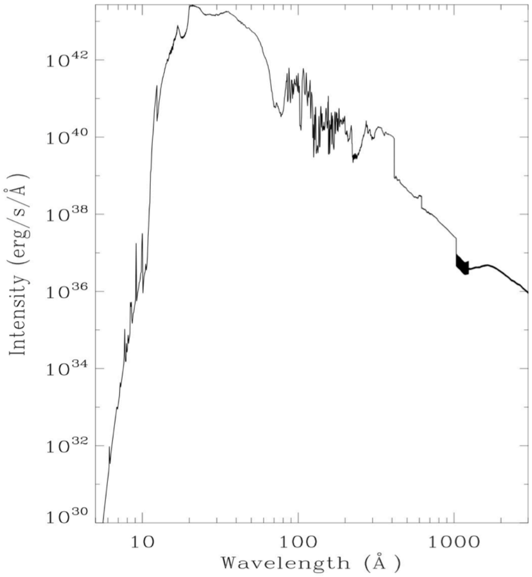


Fig 1. SBO model for a core-collapse SN. Peak flux is found in the soft X-ray and EUV regions.

2.3. Ancillary Targets

Although not drivers of observatory requirements, due to the survey nature of the previous two science cases, important astrophysical targets of various kinds will also be observed. These include lower redshift sub-luminous, short, and long GRBs; thermonuclear bursts; flare stars; SNe Ia breakouts; superfast X-ray transients; classical novae; tidal disruption events; blazars; AGNs; soft γ-ray repeater flares; and hot OB stars with winds, to name a few.

---

[*] Southwest Research Institute; [†] University of Texas, San Antonio; [*] NASA Goddard Space Flight Center; [+] Los Alamos National Lab; [◆] Pennsylvania State University

III. TECHNICAL CAPABILITIES

To address the first science problem, DoMaS requires GRB detection and afterglow instruments that are particularly sensitive to high-z GRBs. For GRB detections at high-z, the optimal instrument is a wide-field soft X-ray telescope (WFSXT) rather than one tuned for the harder X-ray or gamma-rays (cf. 12). Using the new and exciting Lobster-eye technology, such an instrument can achieve sensitivities that are 100 times better than current coded apertures (13). Afterglow follow-up requires a large aperture (~1m) narrow-field near-IR telescope (NIRT) capable of medium resolution slit spectroscopy in order to capture the afterglow at its brightest and maximize the spectral S/N. Based on a fluence of $\sim 10^{-9}$ erg cm^{-2} and field-of-view (FoV) for the WFSXT, convolved with models of high-z GRBs based on *Swift*, *Fermi*, and CGRO data (14), DoMaS would detect ~350 $z>8$ GRBs and ~30 $z>12$ in a 5-year mission.

Tackling the second science question necessitates detection and follow-up spectroscopy of SNe SBO events. As with GRBs, because of their paucity, detecting breakout events requires a wide FoV instrument such as WFSXT. For follow-up spectroscopy, a medium aperture (~50cm) narrow-field far-UV telescope (FUVT) capable of medium resolution slit spectroscopy is required for capturing strong key diagnostic lines. Based on the FoV of the WFSXT and the core-collapse SNe rate (e.g. 15), DoMaS would detect ~400 SBO events out to 100 Mpc in a 5-year mission.

A near-geostationary orbit with telescopes pointed anti-sun is ideally suited for this observatory. The WFSXT will continuously monitor the sky for GRB and SBO events, while the narrow-field instruments observe formerly triggered events or ancillary science targets. When the WFSXT triggers an event, the spacecraft rapidly (~0.5°/s) slews to the target allowing the co-aligned narrow-field instruments to begin immediate observations. Public rapid notifications of the target location, brightness, and redshift are sent through TDRSS to ground-based observers. Key instrument parameters are provided in Table 1. The total cost for the observatory, based on cost models (MICM, NICM, PCEC), is $762M in FY16 dollars.

Table 1. Key Instrument Parameters

Telescope	Energy/ Wavelength	Angular Resolution	FoV	Resolving Power (R)	Sensitivity
WFSXT	0.2-5.0 keV	1 arcmin	2.4 sr	40	1.6×10^{-11} erg cm^{-2} s^{-1}
NIRT	0.7-2.5 µm	1 arcsec	30 arcmin	1000	3.9×10^{-20} erg cm^{-2} s^{-1} Å^{-1} @ 1.6 µm in 1 s
FUVT	130-300 nm	1 arcsec	30 arcmin	1000	2.4×10^{-17} erg cm^{-2} s^{-1} Å^{-1} @ 1700 Å in 1 s

IV. NEW TECHNOLOGIES

With the exception of a GaN microchannel plate (MCP), all technologies are TRL 6 or higher. The GaN MCP is at TRL 4 and is estimated to be at TRL 6 or higher within a 5-year period.

V. PROBE-CLASS MISSION NEED

Because of the rarity of high-z GRBs, a steradian-level FoV is required for the WFSXT. A MIDEX-class mission is not capable of accommodating the required number of WFSXT modules to achieve such a FoV. Rapid high S/N spectroscopic follow-up requires an ~1m NIRT which also cannot be accommodated on a MIDEX. The high-z GRB science objectives are readily met within a probe-class mission.

Simulations show that SBO physics is much more complex than the simple semi-analytic models predict, while full transport calculations reveal that the details of the explosion can also alter the SBO. A high event rate (which can't be done with a MIDEX for the same reason as GRBs), but reasonable narrow-field follow-up is needed to constrain the explosion parameters and extract information about the stars from the observations.

REFERENCES

[1]Johnson, J., et al. 2012, ApJ, 750, 66; [2]Whalen, D., & Fryer, C. 2012, ApJ, 756, L19; [3]Fryer, C., Woosley, S., & Hartmann, D. 1999, ApJ, 526, 152; [4]Belczynski, K., et al. 2014, ApJ, 789, 120; [5]Dominik, M., et al. 2015, ApJ, 806, 263; [6]Bromm, V. 2013, Rep. Prog. Phys, 76, 112901; [7]Ioka, K., et al. 2012, IAUS, 279, 301; [8]Totani, T., et al. 2006, PASJ, 58, 485; [9]Klein, R., & Chevalier, R., 1978, ApJ, 223, L109; [10]Falk, S. 1978, ApJ, 225, 133; [11]Matzner, C., & McKee, C. 1999, ApJ, 510, 379; [12]Burrows, D., et al., 2012, Mem. S. A. It. Suppl., 21, 59; [13]Gehrels, N., et al. 2012, IAUS, 285, 41; [14]Ghirlanda, G., et al., 2015, MNRAS, 448, 2514; [15]Graur, O., Bianco, F., and Modjaz, M. 2015, MNRAS, 450, 905

FORERUNNER for the EVOLVABLE SPACE TELESCOPE (ForEST)

Howard A. MacEwen[a] and Charles F. Lillie[b]
[a]Reviresco LLC, [b]Lillie Consulting LLC

Polidan et al [1] described a large Evolvable Space Telescope (EST) that meets the requirements for the UV-Optical-IR telescopes defined by the Advanced Technology Large Aperture Space Telescope (ATLAST) [2] and High Definition Space Telescope (HDST) [3] studies, which could be affordably developed in an era of flat NASA budgets. This telescope would be developed, launched and operated in several stages over a period of 20-30 years, using on-orbit assembly and servicing technologies to continually increase its collecting area and instrument capability, while spreading its cost over many years to avoid funding peaks that required an inordinate fraction of NASA's astrophysics budget. We propose a probe-class mission that would provide a modified approach to deploying and further enhancing the affordability of the first stage of an EST.

Starting from the concept of an Evolvable Space Telescope (EST) as developed by Northrop Grumman and external team members and embodying a basic principle of EST (affordable and chronologically level development costs), we envision a new approach to the early stages of such a program. The current EST program assumes deployment of the telescope in three phases (roughly five years apart) with increasing scientific capability to complete a 12 to 20-meter space telescope in a halo orbit about the second Sun-Earth Libration Point SEL2. Phase 1 employs a primary mirror (PM) with three hexagonal segments, Phase 2 has a primary with six segments, and Phase 3 has 18 primary mirror segments. If each segment measures 4 meters from flat-to-flat, the result is a 4 x 12 meter off-axis aperture in Phase 1; a 12 meter filled aperture in Phase 2; and a 20 meter filled aperture in Phase 3.

We propose adding an earlier phase to the EST program, called the ForeRunner (ForEST) that would consist of a single hexagonal 4 meter (flat-to-flat) primary mirror to create an off-axis telescope with (probably) a single instrument (most likely a coronagraph) at the prime focus. This Phase Zero telescope would later be augmented by the launch of two additional segments (plus additional instruments, structure, etc.) and their assembly into a complete three segment Phase 1 telescope, essentially the same as in the original EST concept. Phases 2 and 3 would then follow in much the original manner. Note that this strategy would also provide an opportunity for a gradual buildup of the necessary industrial architecture and testing capability (including in space) of its initial products, followed by a long-term production lifetime with an inherent learning curve.

Design of the initial 4 meter mirror segment and the mechanisms needed for its later attachment could provide a significant programmatic and scientific benefit, since it might be possible for ForEST to begin active observations not too long after the deactivation of the Hubble Space Telescope (HST) and while both the James Webb Space Telescope (JWST) and the Wide Field InfraRed Space Telescope (WFIRST) remain in active operation. This would in turn enable continued observations as JWST and WFIRST were reaching the end of their respective lifetimes and the full EST was in deployment and beginning operations as the complete Phase 1 system.

Adopting this strategy will, of course, require paying careful attention to the use of available in-space infrastructure, as it develops to support human exploration and commercial exploitation of space. The future course of this infrastructure development is not clear at this time, but there are several concepts under consideration that could provide the necessary assembly and deployment support, ranging from small to very large. For this White Paper, we need only note two mission concepts under consideration by the NASA Satellite Servicing Capabilities Office (SSCO) [4]:

- At the small end of the scale, the SSCO is soliciting information and concepts for a system known as Restore-L, a servicing spacecraft massing around 1,000 kg or slightly more, and designed to refuel low orbit spacecraft (and perform limited other servicing missions as possible) using remote teleoperation of robotic tools.
- At the large end, the SSCO has described a Human/Robotic Telescope Servicer designed to work in deep space in the company of a manned platform to control the operations and intervene directly if necessary. The mass of this system would be around 30,000 kg.

The needs of affordability for ForEST and the schedule urgency created by the coming retirement of major astrophysical telescope systems certainly seem to favor acquisition of servicing spacecraft from the first of these two classes, although this conclusion is subject to modification dependent upon infrastructure developments that may occur to support human exploration missions. To enable servicing operations throughout cislunar space, and to aid human exploration, a somewhat larger vehicle than Restore-L, massing around 5,000 kg and designated MiniServ [5] in earlier publications, may represent the best selection.

Starting from this context, we propose to conduct a study addressing two mission concepts:

- The ForeRunner Evolvable Space Telescope (ForEST) to serve as an affordable, early Phase Zero of a large EST, such as has been proposed in earlier mission concept studies, and
- The MiniServ Satellite Servicing System and its ability to enable assembly of large space telescopes launched in unassembled states (to reduce mass, risk, and cost) that are capable of only limited amounts of self-deployment.

We believe that the combination of these two mission concepts could accelerate the deployment of new, large astrophysical space telescopes in deep space, enhance their affordability, and reduce the risk of long gaps in space-based astronomy across the UV-Visible-IR spectrum that may follow the completion of the HST, JWST, and WFIRST missions.

REFERENCES

[1] Polidan, R., et al, “An Evolvable Space Telescope for Future Astronomical Mission”, Proc. SPIE 9143-19, Montreal, Quebec, Canada, 2014.

[2] Postman, M., et al., “Advanced Technology Large Aperture Space Telescope; science drivers and technology developments,” Opt. Eng. 51(1), 011007 (2012).

[3] Dalcanton, J., et al., “From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy”, AURA, 2015, http://www.hdstvision.org/s/hdst_report_final_072715.pdf.

[4] Satellite Servicing Capabilities Office, “On-Orbit Satellite Servicing Study: Project Report”, NASA Goddard SFC, Oct 2010.

[5] Lillie, C. and MacEwen, H., “Flexible Servicing in Deep Space – MiniServ”, AIAA SPACE 2014, San Diego, CA, Aug, 2014.

HORUS – THE HIGH ORBIT ULTRAVIOLET-VISIBLE SATELLITE

Paul Scowen, Arizona State University, paul.scowen@asu.edu

Executive Summary

The High-ORbit Ultraviolet-visible Satellite (*HORUS*) is a 2.4-meter class space telescope that will conduct a comprehensive and systematic study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process.

To do so, *HORUS* will provide 100 times greater imaging efficiency and more than 10 times greater UV spectroscopic sensitivity than has existed on the *Hubble Space Telescope* (*HST*). The *HORUS* mission will contribute vital information on how solar systems form and whether habitable planets should be common or rare. It also will investigate the structure, evolution, and destiny of galaxies and universe. This program relies on focused capabilities unique to space that no other planned NASA mission will provide: near-UV/visible (200-1075nm) wide-field, diffraction-limited imaging; and high-sensitivity, high-resolution UV (100-170nm) spectroscopy. Our implementation offers ample opportunity for international participation.

HORUS is designed to be launched into a semi-stable orbit at Earth-Sun L2. From this vantage *HORUS* will enjoy a stable environment for thermal and pointing control, and long-duration target visibility. The core *HORUS* design will provide wide field of view (WFOV) imagery and high efficiency point source FUV spectroscopy using a novel combination of spectral selection and field sharing. The *HORUS* Optical Telescope Assembly (OTA) design is based on modern light weight mirror technology with a faster primary mirror to shorten the overall package and thereby reduce mass. The OTA uses a three-mirror anastigmat configuration to provide excellent imagery over a large FOV. The UV/optical Imaging Cameras use two 21k × 21k Focal Plane Arrays (FPAs) consisting of thirty-six Si 3.5k × 3.5k CCD elements each. The FUV spectrometer uses cross strip anode based MCPs improved from *HST-COS* technology. Fine guidance sensing is accomplished via Si arrays mounted at the Cassegrain focus.

We have baselined a total cost for the mission of $1.28B FY17 including 30% contingency excluding the cost of the launch vehicle, based on a revised cost and technology study conducted at the request of the 2010 Decadal Survey and extrapolated to today. The capabilities and advantages *HORUS* brings to the table are derived from a combination of its aperture, its imaging field of view and its FUV spectral throughput. It could not be done by a MIDEX class mission.

Science Program

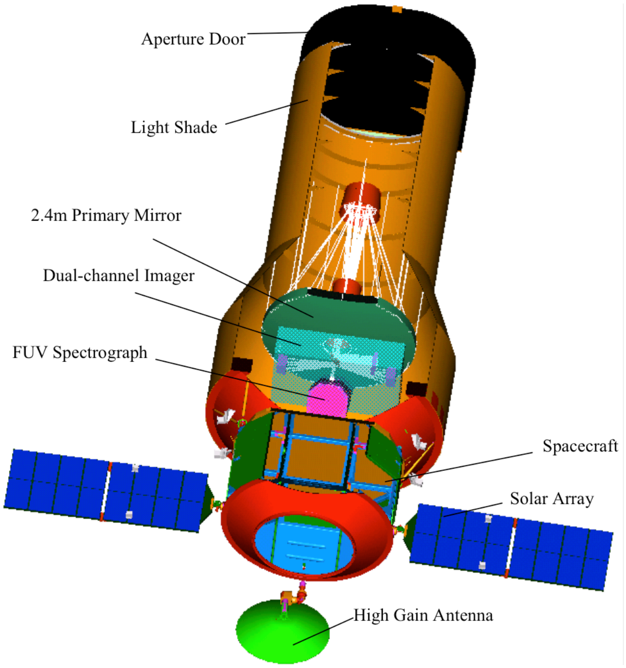
The *HORUS* science program employs a step-wise approach in which both imaging and spectroscopy contribute essential information to our investigation.

Step 1 — Conduct an imaging census of all high-mass star formation sites within 2.5 kpc of the Sun to determine how frequently solar systems form and survive, and develop observational criteria connecting properties of the ionized gas to the underlying stellar population and distribution of protoplanetary disks.

Step 2 — Survey all major star forming regions in the Magellanic Clouds, where we can still resolve relevant physical scales and structures, access starburst analogs, and sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies.

Step 3 — Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed. *HORUS* can observe entire galaxies surveyed by *GALEX* and *Spitzer* with more than 100 times better spatial resolution.

Step 4 — Measure star formation and metal production rates in the distant universe to determine how galaxies assemble and how the elements critical to life such as C and O are generated and distributed through cosmic time.



Horus Origins Science Mission Fact Sheet

Overview:

The HORUS Origins Science Mission is a 2.4m UV-visible observatory orbiting at Earth-Sun L2 that will restore on-orbit imaging and UV spectroscopy to the community to allow the pursuit of an aggressive science program to study star and planet formation in visible star-forming environments in the Milky Way, Magellanic Clouds, and both nearby and distant galaxies.

Science Goals:

1. Characterize global properties and star formation histories in massive star forming regions in the Milky Way.
2. Understand how environment influences the process of star and planet formation.
3. Track the evolution of and derive survivability criteria for low-mass proto-planetary disks in massive star forming regions, similar to where the Solar Nebula likely formed.
4. Spectroscopically detect and characterize extrasolar planets through their UV absorption and emission signatures.
5. Develop a classification scheme for star forming regions based on observable stellar and emission-line diagnostics.
6. Extend the classification scheme to regions that do not have nearby analogs but are common in external galaxies, such as the 30 Doradus region in the Large Magellanic Cloud.
7. Apply the classification scheme to nearby galaxies out to ~5 Mpc to infer the distribution of high- and low-mass star formation over galactic scales.
8. Develop observational criteria (e.g., calibrated Hα and [O II] luminosity functions) for characterizing star formation in high-redshift galaxies, where *Spitzer* and *JWST* observe the rest-frame UV-visible emission in the infrared.

Measurements:

1. Image all massive star forming regions within 2.5 kpc of the Sun through a common set of continuum and emission-line filters with sufficient spatial resolution to distinguish Solar System-scale objects and structures.
2. Identify all exposed proto-planetary disks in nearby massive star forming regions, where most low-mass stars form, and quantify their sizes, orientations, opacities, and distributions.
3. Spectrally search for and identify extrasolar planets as well as infalling cometary material in protostellar systems
4. Survey all massive star forming regions in the Large and Small Magellanic Clouds using the same filter set with sufficient spatial resolution to distinguish structures and processes that have Galactic analogs.
5. Survey a representative sample of Local Group and nearby galaxies – spanning a range of galaxy types, merger histories, and metallicities – using the same filter set with sufficient spatial resolution to distinguish individual star forming sites and internal HII region structure.
6. Extend the scope of the survey to star formation in the distant universe through spectral observations of of Ly-α forest hydrogen clouds and quasars

Performance Requirements and Implementation Summary:

Primary Mirror Diameter:	2.4m (yields ~0.05″ resolution at 5000Å)
Image Scale:	Both 0.1 and 0.05 arcsec/pixel (2 imaging modes)
Wavelength Coverage:	200 – 1000 nm (imaging); 100 – 200 nm (spectroscopy)
Field of View:	14′×14′ (~200 sq-arcmin on 8k×8k CCD array; 25× HST-WFC3)
Wavelength Multiplexing:	Dichroic split at ~510nm; optimized UV-blue and red-NIR channels
Spectral Capabilities:	100 – 200 nm; R=40,000 over a 0.5”x5” slit
Survey Capability:	> 20 sq-degs per yr to surf. brightness of 1×10^{-16} ergs/cm^2/s/arcsec^2
Optical Design:	Three mirror anastigmat
Pointing/Stabilization:	10 (goal), 20 (core) mas over 1000s (similar to *Kepler*)
Filter Set:	Broad-band (R~4), medium-band (R~7), narrow-band (R~100)
Detector Efficiency:	CCD DQE: ~80% at 6563Å; ~60% at 3727Å; ~50% in UV
BB Photometry Accuracy:	1% relative, 5% absolute (nominal CCD performance)
Data Volume & Telemetry:	~80 GB per day raw; Ka-band science return (similar to *Kepler*)
Estimated Mission Cost:	$1.28B FY17 not including LV, based on Decadal 2010 study extrapolated to today
Launch Vehicle:	Delta IV 3-stage (2925-10L) to L2 orbit
Mission Duration:	3-yr nominal mission (~30 month science phase); 3-yr extended mission

Science Team: Paul Scowen, Rogier Windhorst, Steve Desch, Rolf Jansen (ASU), Matthew Beasley (PRI), John Bally (U. Colorado), Daniela Calzetti (STScI), John Gallagher (U. Wisconsin), Patrick Hartigan (Rice U.), Rob Kennicutt (IoA, Cambridge), Tod Lauer (NOAO), Robert O'Connell (U. Virginia), Sally Oey (U. Michigan), Deborah Padgett (GSFC), Jill Bechtold (U. Arizona), Jason Tumlinson (STScI), Melissa McGrath (SETI), Aki Roberge (GSFC), Chris Johns-Krull (Rice U.), Daniel Stern (Caltech), Oswald Siegmund (Berkeley SSL), Shouleh Nikzad (JPL)

Science & Technology Related Missions: *HST-WFPC2, GALEX, Spitzer, Kepler, WISE, HST-WFC3, JWST, WFIRST*

Deep Survey Telescope: Exploring the First Billion Years

Probe-Class Astrophysics Mission Concept

Frederick R. Hearty, PhD   Pennsylvania State University   frh10@psu.edu
H. Philip Stahl, PhD   NASA MSFC

Deep near infrared and time domain discovery space remains largely unexplored in the era of time domain astrophysics, even though the technology exists to do so now. This white paper presents a mission concept for exploring the origin and evolution of large scale structure during the Universe's first billion years by direct observation of the entire sky within that discovery space. Though optimized for this primary science driver, this all-sky NIR and time domain survey will raise the entire astronomical community's data foundation to unprecedented levels. This work draws heavily on the approach and scientific success of the Sloan Digital Sky Survey (its primary science driver was one million galaxy redshifts) and is fully complementary to all operational and planned observatories as well as all completed, in-progress, and planned sky surveys.

Science Drivers

The early Universe is largely known through models and isolated deep observations, neither of which well-predict the assembly of baryons into the earliest structures. The birth epoch of the first super-massive black holes and activation of the first QSOs are unknown observationally, though predicted by existing models to be accessible by existing technology (e.g., large ground-based observatories, JWST). Assembling baryons into the first massive galaxies and clusters, as evidenced by isolated deep observations, appears to have started earlier and progressed much more rapidly than predicted by existing models. Onset of the first Type 1a supernovae (SNe-1a) is a definitive milepost at the end of the first billion years that can be used to empirically establish the end of this early era, yet it has not been observed. *No existing or planned experiment will fully conduct this science.* JWST has the light collecting ability to observe such events as the first QSOs and clusters, and the onset of SNe-1a, but not the field-of-view to routinely discover them and characterize their environments. LSST will successfully explore subsequent generations of such phenomena, but is ultimately limited to moderate redshift by its cutoff at optical NIR wavelengths and the NIR-bright and variable sky. Wavelength limitations also exist for WFIRST-AFTA now that it is baselined on a warm observatory; it will search another micron further into the NIR in a single pass (several filter bands) over 5% of the sky. Only a large-grasp, cold telescope can discover the range of events during the rapidly evolving first billion years and characterize the environments within which they originated.

Therefore, the primary science driver for the Deep Survey Telescope (DST) is, ***"How was large-scale baryonic structure assembled in the early Universe?"*** This is an empirical study -- direct observation in great depth and breadth is used to illuminate our cosmic origins and substantiate existing models. The secondary but not lesser science driver is, ***"Provide a deep, high photometric and astrometric precision, time-domain survey of the entire sky at near infrared wavelengths to enable scientific investigations from planetary science to cosmology."*** In short, DST will chart the observable Universe to discover and understand both its earliest and its rarest phenomena. A few examples of the range of enabled science are provided below.

DST will identify at high redshift:
- The first QSOs
- The earliest massive galaxies and galaxy clusters
- High redshift supernovae of all varieties

DST will identify at low redshift:
- Host galaxy type and redshift for each supernova discovered by LSST
- Progenitor star for many future supernovae from Local Group to Virgo cluster
- Tidal streams and halo structures for Local Group galaxies

DST will identify in our Solar System
- Potentially hazardous asteroids
- Near-Earth asteroids down to 30m
- Planet (and dwarf planet) resident in Kuiper Belt, Inner Oort Cloud, and possibly Oort Cloud itself

Technical capabilities

In order for a simple imaging survey to accomplish such ambitious goals, a combination of technology and operational strategy is needed. A deep NIR survey will detect hundreds of billions of individual objects – notable discoveries can only be isolated from these vast numbers by producing sufficient information to characterize each object… no small task. Spectroscopic follow-on, even when available, would only characterize 1% or so of the objects imaged. A single-epoch of observation using a broadband filters, such as u, g, r, i, and z in the SDSS imaging survey, will enable separation of objects by type and limited-accuracy photometric redhsifts (z_{phot}). Morphology also can be used to separate point and extended sources. Proper motion and parallax measurements can be used to separate near and distant targets.

For DST, the following strategy will be use to fully characterize the majority of identified objects:

1) Precision photometry using 12-16 broadband filters from 0.5-5microns provides spectral energy distribution for object identification and better than 1% accurate redshift (z_{SED}) determination;
2) Precision astrometry and parallax measurements (building on the GAIA catalog) to separate near and distant objects;
3) High spatial resolution to differentiate extended objects from point sources; and
4) Time domain observations to detect and characterize photometric (e.g., QSOs, SNe-1a) and astrometric variability.

This set of observables produced by imaging alone is sufficient to identify and characterize the vast majority of objects detected. Data volume handling and the tools to reduce the data are similar challenges to those being met by the LSST team.

The observatory itself is based on a 4m-class monolithic primary mirror telescope, passively cooled to around 70K. A major 'breaking' of the cost curve is needed to meet Probe-Class guidelines of approximately $1B. Design approaches that have great potential for cost savings and/or minimizing risk:

1) Single imaging instrument with fixed filters as used in the SDSS design (single operating mode)
2) Moderately light-weighted Zerodur substrate mirrors (available in 6-12mo) with integrated CTE-matched carbon fiber telescope structure to allow warm figuring, alignment, and testing (Note: Moderate light-weighting halves the cost compared to ultra-light-weighting). Cast borosilicate mirror is also low cost option.
3) Mirrors figured for infrared imaging observations (Note: λ/8 figuring halves the cost compared to UV/Optical)
4) Liberal mass budget generally used to limit ultra-light-weighting costs
5) Commercially available electronics with fault-tolerant design
6) Near zero on-board software for data processing
7) Commercially available spacecraft SEP buses such as Boeing's 702SP/MP
8) Heavy launch for direct-to-GSO insertion (engineering flight on SLS, or commercially available heavy launcher)
9) Continuous data downlink from GSO instead of Deep Space Network from L2 (laser downlink is baseline)
10) Spacecraft ground control from established facility and team (Swift mission) at Penn State University
11) Science collaboration structure for experiment design, operations planning, and data processing and release derived from SDSS and LSST collaboration models

Based on discussions with AST Division at MSFC, and recent NASA investigations that compared internal development costs with the private sector, substantial reductions in the cost for a large aperture observatory are attainable. The implications of reduced cost for this aperture favorably impact planned observatories (e.g., HabEx) and open the door to significantly more capable experiments.

Technical capabilities of DST will include:

1) Spectral coverage (continuous) 0.5-5 microns; 12-16 filter bands with fixed filters
2) Pixel scale 0.18-0.20 arcsec/pixel, 10 or 15 micron pixels (dithering/Drizzling to improve spatial resolution)
3) Pointing accuracy <5mas
4) Field of View nominally 1.6 degrees on a side, 2.5 sq. degrees
5) Sensitivity ~27mag in 60 s integration
6) Single operational mode – imaging survey; sample-up-the-ramp non-destructive reads
7) Design reference mission (nominal year of survey)
    a. Galactic Caps (~20,000 deg^2) 1 visit @60s (~7.5 mo.), 27.0 ABmag each filter
    b. Galaxy Plane (~20,000 deg^2) 1 visit @20s (~2.5 mo.), 26.4 ABmag each filter
    c. Deep Field (~2x100 deg^2) 13.5 visits (~1.0 mo.), ~800s + above, 28.5 ABmag
    d. Ultra Deep Field (~2x10 deg^2) 135 visits (~1.0 mo.), ~8,000s + above, 29.5 ABmag
8) Mission lifetime: ten years with a substantial guest investigator program; five years minimum without

New technologies

No new detector technologies, beyond those being developed for WFIRST-AFTA, are required. Fine steering mirror for large field is needed; available at smaller scale, but not yet confirmed for this application. Rapidly developing commercial applications for laser downlink, technology demonstrations NASA (OPALS, LLDC), and ESA (EDRS) can be leveraged.

Probe-Class Mission Needed?

The large-aperture observatory required to exploit the NIR, time domain discovery space dictates a Probe-Class mission. Such an observatory would fall under flagship status without extreme effort to simplify experiment design, followed by building to cost. Smaller aperture designs have insufficient grasp to accomplish this science.

The Space High-Angular Resolution Probe for the InfraRed (SHARP-IR): A Potential Far-Infrared Interferometric Probe

S. Rinehart, M. Rizzo, D. Leisawitz, L. Mundy, J. Staguhn. A. Dhabal, R. Juanola-Parramon, D. Fixsen, E. Sharp, D. Padgett, K. Stapelfeldt, M. DiPirro, E. Mentzell, S. H. Moseley, J. Mather, A. Roberge, M. Cordiner, S. Milam

The Space High-Angular Resolution Probe for the InfraRed (SHARP-IR) would extend high resolution imaging into the far IR, observing crucial atoms, ions, and molecules such as water as well as continuum sources, to enable discoveries in the areas of star and planet formation, AGN, obscured star forming galaxies at high redshifts, cool objects in general, and the outer solar system. With a cold interferometer and a baseline of 12 m, it would offer 8 times the spatial resolution of Herschel combined with superior (TBD) sensitivity. It would operate between 20 and 160 μm, filling the *u-v* plane in the synthetic aperture, to enable high quality imaging. This new concept is currently under development at GSFC, with a (growing) science team from multiple institutions; the mission is in the earliest stage of concept development, as the team works to identify key engineering challenges and to define the core science that would be enabled by it.

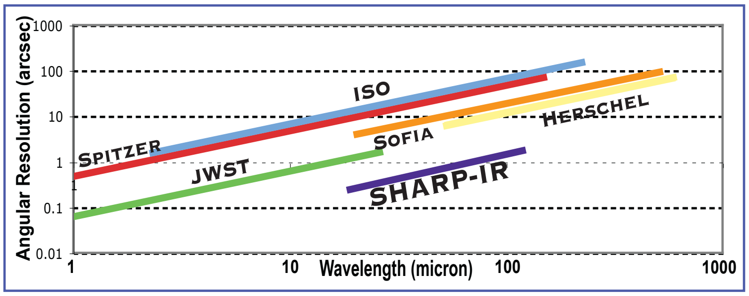
1. Science Drivers

A far-infrared (FIR) space-based interferometer such as SHARP-IR would provide new capabilities for high angular resolution in the FIR; these capabilities, in turn, would enable a wide range of new scientific inquiry. While the science case for SHARP-IR is still in development, one key area will be the study of star formation. Most stars in our galaxy form in clusters of 50 or more young stars. Because of their young age, a large amount of dusty material from the original molecular cloud still surrounds these stellar nurseries, and absorbs short wavelength light to re-radiate it in the thermal infrared: that is why these regions are best studied at infrared wavelength. However, the protostars are often in close proximity, such that the long wavelength observations made with *Spitzer, Herschel*, and SOFIA are often confused: it is not possible to clearly identify where the far-IR emission is coming from, and this leaves key questions about the star formation process unanswered. With the angular resolution provided by SHARP-IR, it would become possible to not only measure the spectra of a large number of protostars, but it would also allow direct measurement of the shapes of the envelopes around Young Stellar Objects (YSOs). This will enable us to map the distribution of dust and help answer fundamental questions about how protostars reach their final mass in these important regions of stellar birth. In addition, SHARP-IR would enable new studies of the processes present in the hearts of active galactic nuclei, dynamics and interactions near our own galactic center, and characterization of bodies within our own solar system.

As part of the ongoing SHARP-IR study, we are looking at all of these scientific options, and are expanding the science team to explore other potentially new and interesting science.

2.Technical Capabilities

The goal of the SHARP-IR concept is to complement JWST by providing comparable angular resolution observations out to much longer wavelengths (as can be seen in the figure above). SHARP-IR will take advantage of interferometric data reduction techniques developed for radio astronomy, and will provide nearly an order of magnitude improvement in angular resolution relative to *Herchel*, with comparable sensitivity. One activity within the current SHARP-IR study effort is the development of simulations that clearly demonstrate these capabilities.



3. New Technologies

Fundamentally, no new technologies are necessary for SHARP-IR, with the possible exception of detectors. The fast response times and high sensitivity needed from detectors are likely well within the reach of current detector development programs, but additional analysis of detector requirements will be needed as study progresses. Beyond detectors, all of the major technologies have been proven, and the BETTII balloon experiment will serve to provide a system-level demonstration of a free-flying interferometer. Further, independent of the final architecture of the FIR Surveyor, investments in technologies (e.g. cryocoolers) will likely benefit SHARP-IR; while the current state-of-the-art is sufficient for SHARP-IR, improved subsystem capabilities will reduce cost and risk.

4. Why a Probe?

There are several motivations for SHARP-IR. Scientifically, an order of magnitude improvement in angular resolution at FIR wavelengths opens a new space of discovery. But SHARP-IR would also serve as a technological pathfinder. In 2012, NASA HQ established the NASA Roadmap team, leading to the Roadmap report, *Enduring Quests – Daring Visions*. In that document, a series of missions are laid out, first in the Formative Era, to be followed by missions in the Visionary Era. Notably, “All notional missions in the Visionary Era are interferometers, and technology maturation of interferometric techniques is thus highly relevant to realizing the science vision.” The report also notes "Interferometry has historically progressed from longer wavelengths, where technological challenges are less extreme, to shorter wavelengths.”

It is possible that the FIR Surveyor could adopt an interferometric architecture; should that occur, it would have capabilities exceeding that of SHARP-IR, and would enable future interferometers working at shorter wavelengths (as per the vision of the Roadmap). If, however, the FIR Surveyor adopts a single aperture architecture, a mission such as SHARP-IR is needed to make future interferometric observatories possible.

Balloon-based experiments such as BETTII serve as an important stepping stone to future space-based missions, but limitations of flying within the atmosphere fundamentally constrain their scientific capability. Most importantly, the warm telescopes that must be used on a balloon interferometer limit the overall sensitivity, such that they can observe only the closest star formation regions.

We have also considered whether a mission similar to SHARP-IR could be developed on an Explorer budget, but previous experience with mission studies of other interferometric missions (SPIRIT, at >$1B; FKSI, at ~$500M in 2009 dollars) demonstrated that these small budgets are not commensurate with a scientifically capable interferometer.

ORION^{II}

UV-VISIBLE PROBE

Paul Scowen, Arizona State University, paul.scowen@asu.edu

Orion is a 1.2-meter class space telescope that will conduct the first-ever high spatial resolution survey of a statistically significant sample of visible star-forming environments in the Solar neighborhood to answer the question "**How often do solar systems form and survive in massive stellar environments?**". Within the Probe-class mission cost envelope *Orion* will provide 100 times greater imaging efficiency than currently exists on *HST*.

The *Orion* mission has a well-defined scientific program at its heart: a statistically significant survey of local, and intermediate sites and indicators of star formation to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process. This program relies on focused capabilities unique to space and that no other planned NASA mission will provide: near-UV/visible (200-1100nm) wide-field, diffraction-limited imaging.

Observing efficiency. The *Orion* imager has a field of view (FOV) of ~200 square-arcminutes, uses a dichroic to create optimized UV/blue and red/near-IR channels for simultaneous observing in 2 bandpasses, and employs modern detectors with substantial quantum efficiency gains, especially at red wavelengths, over the CCDs used in *HST's* cameras. We estimate discovery efficiency gains of factors of 100 for imaging with *Orion* relative to *HST* based on our design and assuming an Earth-Sun L2 orbit that provides long target visibility.

Necessary Technology. To deliver the performance cited for this mission, a new class of CCD detector is being developed with our partners at JPL to deliver DQE levels down to the blue edge of silicon that will match the DQE performance in the red, allowing us to build the Observatory with a dichroic splitter to simultaneously observe in the red and blue without taking a hit in observing efficiency or the quality of the images produced. The required technologies currently stand at a TRL of 4-5.

Mission Scale. This mission has been priced twice through Team X studies and has been found to exceed the *MIDEX* cost cap as currently defined ($250M FY 17) and therefore requires the Probe-class mission line to be possible.

Science investigation. We employ a step-wise approach to our observing program in which both imaging and spectroscopy contribute essential information to our investigation.

Step 1 — Conduct a census of all high-mass star formation sites within 2.5 kpc of the Sun to determine how frequently solar systems form and survive, and develop observational criteria connecting properties of the ionized gas to the underlying stellar population and distribution of protoplanetary disks.

Step 2 — Survey all major star forming regions in the Magellanic Clouds, where we can still resolve relevant physical scales and structures, access starburst analogs, and sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies.

Step 3 — Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed. *Orion* can observe entire galaxies surveyed by *GALEX* and *Spitzer* with more than 100 times better spatial resolution.

Unique science that can only be conducted by *Orion*:

Precision Photometry: *Orion* provides a wide FOV with 0.05 to 0.1 arcsecond angular resolution. Stable PSFs combined with a stable focal-plane geometry will permit unprecedented precision in astrometry and photometry.

Outflow and Nebular Motions: The exquisite proper motion sensitivity of *Orion* will enable unique measurements of the motions of supersonic protostellar outflows and stellar wind bubbles to a distance of several kpc; the mildly supersonic motions of expanding HII regions to about 1 kpc; as well as the motions in planetary nebulae and supernova remnants.

The *Orion* survey of the Magellanic Clouds will be unique in its powerful combination of angular resolution, depth, and spatial coverage. Each of the Magellanic Clouds survey components is designed to obtain significant coverage in its domain. The broadband survey will be essentially complete in area coverage; the narrowband survey will cover 5% and 14% of the LMC and SMC, respectively, plus a sample of HII regions representative of the range of star-forming conditions in these galaxies.

Extragalactic stellar populations contain the histories of evolution of the baryonic components of galaxies. Challenges include the presence of multiple stellar population components along each sightline, effects of interstellar dust on observed SEDs, and the relatively low brightnesses of outer regions of galaxies relative to the sky. The *Orion* combination of a 14 arcmin FOV, high angular resolution, simultaneous access from the MUV to the NIR, and low sky background allow us to address all of these issues.

Orion Probe Mission Fact Sheet

Overview:

The *Orion* Probe mission is a 1.2m UV-visible observatory orbiting at Earth-Sun L2 that will conduct the first-ever high spatial resolution survey of a statistically significant sample of visible star-forming environments in the Milky Way, Magellanic Clouds, and nearby galaxies.

Science Goals: **"How frequently do solar systems form and survive?"**

1. Characterize global properties and star formation histories in massive star forming regions in the Milky Way.
2. Understand how environment influences the process of star and planet formation.
3. Track the evolution of and derive survivability criteria for low-mass proto-planetary disks in massive star forming regions, similar to where the Solar Nebula likely formed.
4. Understand the range of star and planet formation environments and how that dictates the range of masses, ages, and other important properties of resultant stars and planets
5. Leverage survey results from missions such as *Kepler* and *Spitzer* to allow characterization of observed stellar populations in concert with measured dynamical properties of the stars.

Measurements:

1. Image all massive star forming regions within 2.5 kpc of the Sun through a common set of continuum and emission-line filters with sufficient spatial resolution to distinguish Solar System-scale objects and structures.
2. Temporally monitor stars in regions to characterize the resulting stellar population, spectral type, binarity, accretion rates, rotation rates, jet dynamics, age and mass all as a function of environment.
3. Identify all exposed proto-planetary disks in nearby massive star forming regions, where most low-mass stars form, and quantify their sizes, orientations, opacities, and distributions.
4. Survey all massive star forming regions in the Large and Small Magellanic Clouds using the same filter set with sufficient spatial resolution to distinguish structures and processes that have Galactic analogs.
5. Survey a representative sample of Local Group and nearby galaxies – spanning a range of galaxy types, merger histories, and metallicities – using the same filter set with sufficient spatial resolution to distinguish individual star forming sites and internal HII region structure.

Performance Requirements and Implementation Summary:

Primary Mirror Diameter:	1.2m (yields ~0.1″ resolution at 5000Å)
Image Scale:	0.1 arcsec/pixel
Wavelength Coverage:	200 – 1000 nm
Field of View:	14′×14′ (~200 sq-arcmin on 8k×8k CCD array; 25× HST-WFC3)
Wavelength Multiplexing:	Dichroic split at ~510nm; optimized UV-blue and red-NIR channels
Survey Capability:	> 20 sq-degs per yr to surf. brightness of 1×10^{-16} ergs/cm^2/s/arcsec^2
Optical Design:	Three mirror anastigmat
Pointing/Stabilization:	10 (goal), 20 (core) mas over 1000s (similar to *Kepler*)
Filter Set:	Broad-band (R~4), medium-band (R~7), narrow-band (R~100)
Detector Efficiency:	CCD DQE: ~80% at 6563Å; ~60% at 3727Å; ~50% in UV
Required Technology Maturity:	Both CCDs and optic elements are at TRL 4-5
BB Photometry Accuracy:	1% relative, 5% absolute (nominal CCD performance)
Data Volume & Telemetry:	~80 GB per day raw; Ka-band science return (similar to *Kepler*)
Esimated Mission Cost:	$358M FY17, excluding LV, based on Team X studies (2) extrapolated to FY17
Launch Vehicle:	TBD to L2 orbit
Mission Duration:	3-yr nominal mission (~30 month science phase); 3-yr extended mission

Science Team: Paul Scowen, Rogier Windhorst, Steve Desch, Rolf Jansen (ASU), Matthew Beasley, (Planetary Resources Inc.), Daniela Calzetti (U. Massachusetts), Patrick Hartigan (Rice U.), Robert O'Connell (U. Virginia), Sally Oey (U. Michigan), Deborah Padgett (GSFC), Mark McCaughrean (U. Exeter, UK), Nathan Smith (U. Arizona), Shouleh Nikzad (JPL)

Science & Technology Related Missions: *HST-WFPC2, HST-WFC3, GALEX, Spitzer, Kepler, WISE, JWST, WFIRST*

Cosmic Dawn Intensity Mapper
- A Probe Class Mission Concept for Reionization studies of the universe.

Asantha Cooray (U. of California Irvine, acooray@uci.edu)
Jamie Bock (Caltech), Denis Burgarella (LAM, France), Ranga Chary (IPAC), Giovanni Fazio (CfA), Andrea Ferrara (SNS, Italy), Yan Gong (UCI), Mario Santos (SKA; Western Cape), Marta Silva (Groningen), Michael Zemcov (RIT)

The proposed NASA Probe Class Mission *Cosmic Dawn Intensity Mapper* (CDIM) will be capable of spectroscopic imaging observations between 0.7 to 6-7 microns in the near-Infrared. The primary science goal is pioneering observations of the Lyman-α, Hα and other spectral lines of interest throughout the cosmic history, but especially from the first generation of distant, faint galaxies when the universe was less than 800 million years old. With spectro-imaging capabilities, using a set of linear variable filters (LVFs), CDIM will produce a three-dimensional tomographic view of the epoch of reionization (EoR), mapping Lyα emission from galaxies and the intergalactic medium (IGM). CDIM will also study galaxy formation over more than 90% of the cosmic history and will move the astronomical community from broad-band astronomical imaging to low-resolution (R=200-300) spectro-imaging of the universe.

Apart from few observational breakthroughs, and all-sky averaged statistics such as the optical depth to reionization with CMB polarization, we have very little information on sources and astrophysics during reionization: (a) what sources are responsible for reionization, (b) what is the initial mass function of stars in first galaxies? (c) was there an appreciable contribution to the UV budget from active galactic nuclei (AGNs)? (d) what is the formation path of supermassive blackholes and first quasars?; and (e) when did metals start to appear?, among many others. EoR will remain the cosmic frontier of the next decade, with new observatories and instruments making key discoveries on the presence and formation of first galaxies and AGNs. While the primary focus is EoR, CDIM is also designed to study galaxy formation and evolution throughout the cosmic history. It will map out, for example, Hα emission from z=0.2 to reionization, providing a three-dimensional view of the star-formation history, its environmental dependence, and clustering over 90% of the age of the Universe.

While JWST is capable of targetted spectroscopy studies of galaxies present in reionization, and survey order 10 sq. arcmins for reionization galaxies, CDIM will make use of tomographic intensity mapping of spectral emission lines to study the aggregate statistical properties of the sources and their spatial distribution. The Lyα and Hα lines will serve as tracers of EoR galaxy formation. They are also sensitive to the rate of star formation. The intensity of these lines, combined with others, will also provide critical clues to the formation of metals in the universe. The tomographic maps of the EoR with CDIM in Lyα and Hα (Silva et al. 2013; Pullen et al. 2014; Comaschi & Ferrara 2016) will complement the planned attempts from ground-based low-frequency radio interferometers to image the EoR with 21-cm line (Chang et al. 2015). Lyα and Hα can separate the tomographic 3D maps to study signal from galaxies independent of the IGM and to study radiative transfer effects associated with the propagation of Ly-α photons during EoR. The proposed wavelength coverage of 0.7 to 6-7 microns is adequate to remove contamination from low-redshift Hα/OIII etc lines for EoR studies (Gong et al. 2014).

When combined with 21 cm tomographic measurements, such as the low-frequency Square Kilometer Array (SKA), proposed tomographic spectral line maps will also probe the physical state of the IGM. For example, Lyα/Hα lines from galaxies is expected to anti-correlate with 21 cm emission from neutral hydrogen in the IGM on a size scale proportional to the ionization ‘bubbles’ carved out of the neutral IGM by UV photons, a measure that is sensitive to the ionization history of the IGM. CDIM will not only establish that anti-correlation, it will measure the average bubble sizes during EoR, establish bubble size distribution function, and study the growth of ionization bubbles from z=8 to 5. Given that the 21-cm imaging with SKA-low and other 21-cm experiments like HERA are likely to be foreground-limited, the combination with an external tracer (such as Lyα and Hα as feasible with CDIM) will likley become crucial to fully extract information on EoR (Chang et al. 2015).

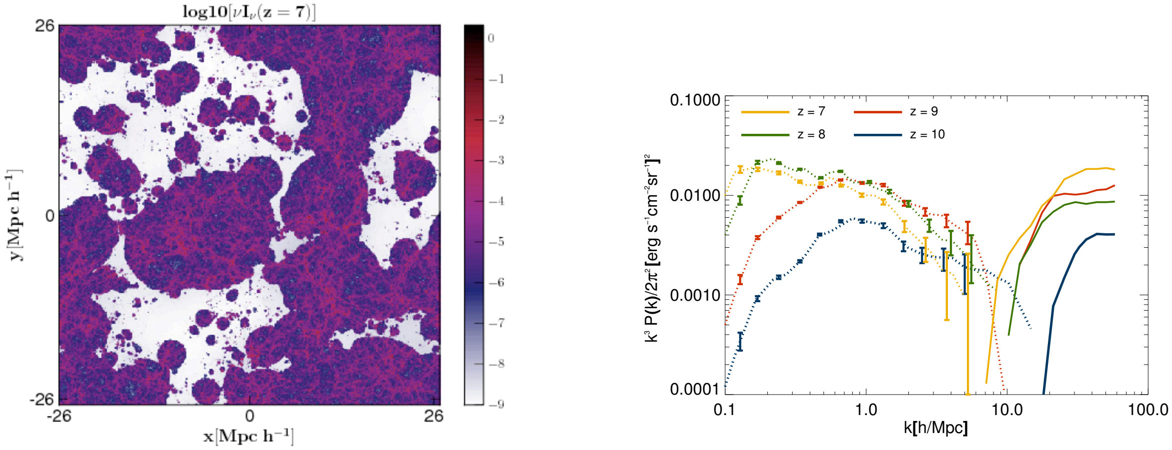


Figure 1. (Left) Simulated Lyα intensity map at z=7, with signal from both galaxies and IGM. (Right) The 21-cm and Lyα cross power spectra at z=7 to 10. The plotted error bars are for a cross-correlation with 15 sq. degree of data with a setup similar to CDIM (Silva et al. 2013).

Mission Summary:

a) CDIM will be a 1.3-1.5m class aperture, passively cooled telescope operating between roiughly 0.7 to 6-7 microns, making use of HgCdTe detectors + sensitivity out to 6-7 microns.

b) R=200-300 spectroscopic imaging over ~10 sq. degree instantaneous FoV, at 1 arcsecond/pixel. R>200 results in $\Delta z < 0.1$ during the EoR between z=6 to 8.

c) Instead of a dispersion element, CDIM will make use of fixed linear variable filters (LVFs) to image the sky at narrow wavelengths. R=250 between 0.7 to 6-7 microns will result in close to ~100 redshift slices during EoR in Lyα and Hα. The full survey will require close to 300 individual pointings towards a given line of sight with pointings offset by the LVF position. Pointing and survey stratgey will be achieved as part of the spacecraft operations without any moving parts in the focal plane. Pointing requirement of the spacecraft, better than 2 arcseconds, is adequate for the mapping necessary.

d) CDIM will carry out two surveys over a 4-5 year period: order 1000 sq. degrees shallow survey and a deeper 100 sq. degrees deep survey. Latter will be for combination with SKA-low or other 21-cm interferometric experiments. Deep survey/instrumental requirement is a line sensitivity better than 10^{-18} erg s^{-1} cm^{-2}.

Cost Estimate: A reliable cost is impossible to achieve at these early stages. Based on the aperature, L2 operations over 4-5 years, data volume, number of detectors, and a comparison to costing of a concept similar to CDIM for ESA M5, we estimate cost to be around $850M.

References: Chang et al. 2015, arXiv.org:1501.04654; Comaschi & Ferrara 2016, MNRAS, 455, 725; Gong et al. 2014, ApJ, 785, 722; Pullen et al. 2014, ApJ, 786, 111; Silva et al. 2013, ApJ, 763, 132.

A Near-IR All-Sky Spectroscopic Probe

M. Robberto (STScI & JHU), Y. Wang (IPAC-Caltech)

Astrophysics in the next Decade will be transformed by the advent of a new generation of facilities producing "all-sky" imaging surveys, e.g. LSST, Euclid and WFIRST. The scientific potential of their data products is enormous. WFIRST will take Hubble-like images over a field 200 times larger than WFC3 on HST. LSST will open a new window on time-domain astrophysics.

In this scenario, JWST and later UVOIR, with their unique sensitivity and spatial resolution, will provide the ultimate follow-up capability. However, the full fruition of these enormous photometric datasets, generally obtained in a handful of broad-band filters, will also exacerbate the need for complementary spectroscopic information. A deep spectroscopic all-sky survey in the near IR would represent the ideal solution. This regime provides critical information for extragalactic (due to cosmological redshift), as well as low-redshift and Galactic studies (to mitigate the effect of extinction); it is also optimally accessed from space, due to the strong limitations imposed by the atmosphere, both absorption and emission.

Years ago we identified a viable mission concept to perform a spectroscopic all-sky survey of the Universe in the near-IR (about 1-1.8micron) [1,2]. Our proposal, the Spectroscopic All Sky Cosmic Explorer (SPACE) had two key science goals: first, to perform the most accurate measurement of the expansion history of the Universe (using baryonic acoustic oscillations) and the growth history of cosmic large scale structure (using redshift space distortions), measuring the redshifts of ~500 million galaxies regardless on their spectral type and environment. In practice, this means building a 3D map of the observable Universe. Second, to understand galaxy build-up and evolution by analyzing the detailed information contained in the same spectra. To reach AB~23 mag continuum with a 1.5m class telescope in ~15min exposures one has to exploit the low sky background and eliminate source confusion. We thus envisioned a spectroscopic instrument operating in slit-mode through MEMS devices. Our approach was similar to the one adopted by NIRSpec on JWST, but instead of Micro-Shutter-Arrays we proposed using Digital-Micromirror-Devices (DMDs), a much more mature technology.

The SPACE proposal was submitted in 2007 by a joint European-US team to ESA for the first cycle of ESA Cosmic Vision 2015-2025; it was selected together with another mission concept, DUNE; they were immediately merged into Euclid. ESA funded an initial space qualification program for DMDs, but soon realized that the assessment phase was incompatible with the planned 2018 launch date for Euclid. Euclid was thus de-scoped to implement a basic slitless spectroscopic capability, aiming at a much less ambitious science program [3].

ESA space qualification program eventually indicated that DMDs are viable for flight [4]. More recently, NASA has funded a SAT program that is delivering promising results [5]; we expect that DMDs may soon be regarded as a TRL 6 technology. If the DMD flight readiness is confirmed, and considering that no other mission concept is planned with similar capability and unique science (both Euclid and WFIRST are designed for slitless spectroscopy), it would be compelling to reconsider the idea of an all-sky spectroscopic survey based on this technology.

The original design of SPACE may provide an initial baseline. It was centered on a 1.5m primary mirror feeding four identical spectrographs. Each spectrograph uses a Cinema-2K DMD as slit selector, with 2.1 million elements to synthetize hundreds of ~0.75" width slits; the total FoV was about 0.4 square degrees. The spectral range was set to 0.8-1.8 micron using a prism, with resolving power set to R~400; other combinations are of course possible and should be considered.

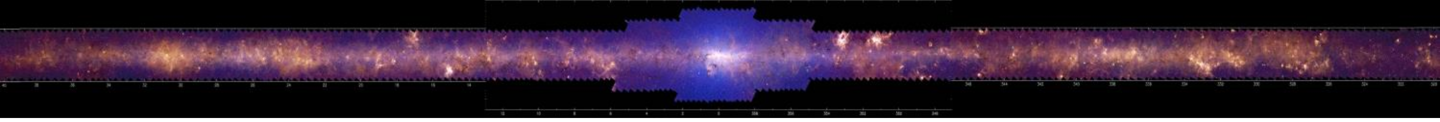
The mission profile was centered on an all-sky survey at galactic latitudes > ±18° (~70% of the celestial sphere). This corresponds approximately to 28,500 square degrees and 71,000 satellite pointing. Assuming 20 min per pointing and an observing efficiency of 75%, this would require 2.7 years. The expected number of galaxy spectra with a 1/3 target random sampling was estimated to be about 500 million. The acquisition of the spectroscopic targets could be done using a catalog, or even directly on board through processing of a preliminary acquisition image in the H-band. The cost of the mission was estimated at the upper limit for a small ESA mission and required contributions from national agencies and possibly NASA. It should now safely fall within the range of a NASA Probe (<$1B).

A fresh study of a SPACE-like mission would require a reassessment of the science case for an all-sky spectroscopic NIR survey; this would easily encompass all fields of Astrophysics. In particular, it would be necessary to address the latest advances on dark energy, the complementarity to other future space missions, LSST and large ground based surveys; the scientific potential for Milky Way studies, originally excluded by the declination cut, should also be discussed. The optimal system parameters, starting with bandpass and resolving power, should be re-evaluated.

It should be possible to benefit from the substantial amount of work already done for SPACE, both in Europe and in the USA; this is documented in a variety of studies, reports and referred papers [6]. In particular, the simulation and analysis tools already developed in support of SPACE could serve as a productive starting point of detail studies for a Spectroscopic Probe.

References:

[1] Robberto & Cimatti 2007, Nuovo Cimento B, 122, 1476; [2] Cimatti, Robberto et al., 2009, Exp.Astron. 23, 39; [3] Laureijs et al. 2010, arXiv:1110.3193; [4] Zamkotsian et al. 2010, SPIE 7731E, 30Z; [5] Travinski et al. 2016, SPIE 9761-7; [6] Wang et al. 2010, MNRAS 409, 737.



Terahertz Space Telescope:

A Far-Infrared Surveyor of Cosmic Origins and Destiny

Christopher K. Walker, University of Arizona, I. Steve Smith, SwRI, Paul F. Goldsmith JPL

The Terahertz Space Telescope utilizes breakthrough inflatable technology to create a large-aperture far-infrared observing system at a fraction of the cost of previous space telescopes. As a follow-on to JWST, TST will revolutionize our understanding of the origin and evolution of galaxies, stars, and the interstellar medium.

The Far Infrared/Terahertz Regime: Pulling Back the Cosmic Veil

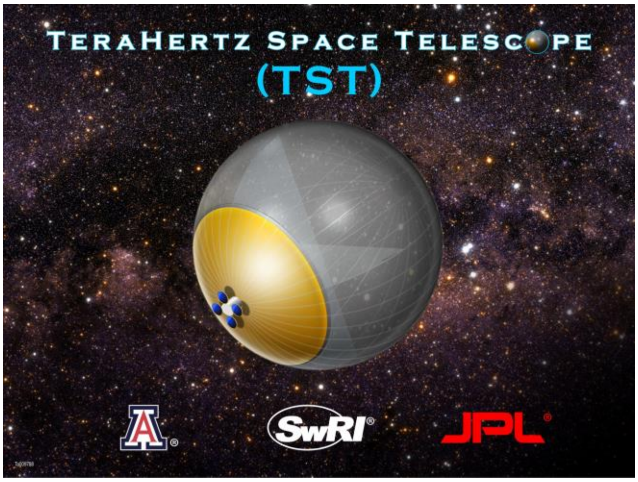
The FIR/THz spectral region holds unique clues to the processes that formed stars and galaxies, and thus is key to answering fundamental astrophysical questions of the origin and destiny of the cosmos. Prior and planned space telescopes have barely scratched the surface of what can be learned in this wavelength region. TST is an affordable 20-30m aperture FIR/THz telescope concept that can explore this regime in unprecedented detail and is an excellent match to the Astrophysics Visionary Roadmap.

TST Science Themes:

- Star formation through cosmic time
- Galaxy formation and evolution: from quasars, Seyferts, and starbursts to the Milky Way
- Life cycle of the interstellar medium
- Galactic ecology
- Astrochemistry
- Formation of solar systems: debris disks, protoplanetary evolution, Kuiper Belt objects, asteroids and comets, planetary atmospheres

Inflatable Technology: Large Aperture at Low Cost

TST will pick up where JWST leaves off: At ~30µm, TST will have >3x the sensitivity and angular resolution of JWST. TST can achieve this at low cost through innovative use of inflatable technology. A recently-completed NIAC Phase II study (Large Balloon Reflector) validated, both analytically and experimentally, the concept of a large spherical reflector integrated into a transparent inflatable structure, and demonstrated all critical telescope functions.



Mission:

Duration: 3-4 years
Orbit: Sun-Earth L2
Launch readiness: 2024
Mission type: Probe-Class; estimated cost < $750M

Spacecraft:

Attitude Control: 3-axis stabilized
Pointing requirements: ~0.1 arcsec
Launch mass: ~600 kg
Launch dimensions: ~2 x 4 m
Max downlink rate: ~10 Mbps, K_a-band

Instrument Module:

Telescope: 20 m inflated, spherical reflector
Frequencies: ~1 to 10 THz (300 to 30 µm)
Angular resolution: ~0.4 to 4 arcsec
Instruments:
Active Spherical Corrector
Coherent & incoherent cameras
  Sensitivity: ~500 K DSB; $\sim 1\times10^{-18}$watt/Hz$^{1/2}$
  Spectral resolution: $\sim 10^6$ to 10^3
Cryogenic system: 2- cryocoolers (4 to 6 K)
Power: ~1 kW, mass: ~225 kg
Heritage: Herschel, SOFIA, STO, LBR

White Paper In Response To NSPIRES RFI For The Next Generation Space UV-Vis Space Observatory (NG-SUVO)

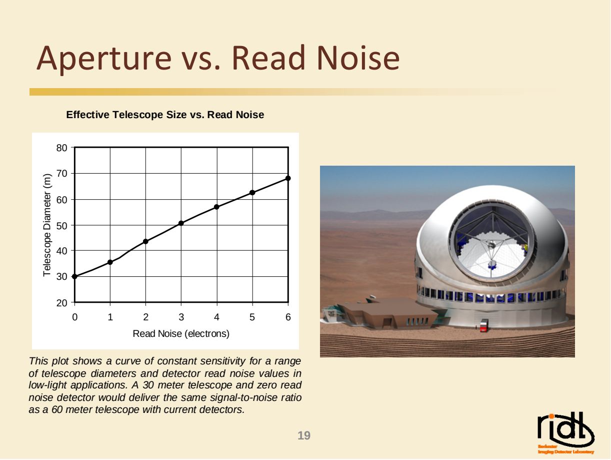
by Mel Ulmer, Northwestern University

In a SPIE paper (Ulmer, 2009, Proc SPIE, 7222, 33) Ulmer outlined a 8-m telescope proposal with upgraded detectors and coating that would, in the UV range, be $\sim 100\times$ more sensitive than HST. However, funding circumstances have changed such that it would appear that a 2.4 m class telescope is about as "good as it gets." Thus, here we de-scope that mission to a 2.4m that would probably cost about \$2G in today's dollars. The main point of the technology discussion that I present first is that vast improvements can be had in the optics and detectors such that a new mission, although not our "dream machine" would bring a factor of > 10 improvement. Second, I demonstrate that plenty of science can be done with a $> 10\times$ improvement.

1 Improvements With Technology Enhancements

For the details of the HST optics see Ford et al 1998 (Proc SPIE, 3356, 234 and references therein). From Ford et al we note that the transfer mirrors **IM2** and **IM3** produce net 34% efficiency at 350 nm. Then by removing the correcting **IM2** and **IM3** mirrors we can greatly improve optics efficiency over the HST system by about $3\times$. The optical telescope assembly (OTA) itself is only 62% @350 nm such that assuming an improvement to 70% is plausible. Then, let us improve by $\sim 2\times$ over the QE of WFC (about 40%) to give us a net gain of about 7 at 350nm. Thus, there is plenty of headroom for the UV even if a CCD is used.

In comparison, the microchannel plates (MCPs) on the HST only about about 5% net QE. The equivalent single photon detectors that will become available (*if NASA ever finds enough money to fund them from TRL3 to TRL6 or above*) that are GN based will be $\sim$ 70%. The gain over the HST would be at least 15 just with a detector advance! Then this system would allow us to do in 40 orbits what it takes HST 600. *Note in comparing with the MCP to the GaN APD, we are comparing zero read noise devices.* Having zero read noise vs CCDs with (say 3 electron read noise) *is important*, however, as shown in Fig 1 taken from web posted presentation given by Don Figer of RIT.



Aperture vs. Read Noise

Effective Telescope Size vs. Read Noise

This plot shows a curve of constant sensitivity for a range of telescope diameters and detector read noise values in low-light applications. A 30 meter telescope and zero read noise detector would deliver the same signal-to-noise ratio as a 60 meter telescope with current detectors.

Figure 1: Read noise versus effective aperture

We see in Fig 1 that going from ~ 3 electrons (the WFC3 UV-Vis) camera to a zero-read-noise one gives us a boot of 50/30. Therefore, if we compare with an avalanche photodiode (APD) GaN zero-read-noise camera to a 40% QE CCD vs the 5% MCP we still get a gain of 50/30 by going to zero read noise. Including the 70%/40% gain in QE for the APD vs the CCD, the net is nearly 3. We are being conservative here in that the GaN does not require the severe blocking filters needed for cameras that are sensitive in the visible. Remember, we gain another factor of 3 by removing the transfer mirrors to then yield a gain of 9 over the current ACS/WFC in the near UV. Assume a 10% improvement in the OTA reflectivity to give an overall factor of 10 improvement; so in 100 orbits the next generation space UV-visible observatory (NG-SUVO) would be equivalent to the 1,000 orbits with HST!

Turning now to the Vis channels on HST: These only cover a field of view of about 3 arc min × 3 arc min. Yet, it should possible to gain a sky coverage factor of 4 with a 6 arc min × 6 arc min FOV. Then, combining zero read noise with the effective increase in étendue of the new mission would yield and improvement of about 6 total. This assumes no improvement in the reflectivity of the OTA, but a 10% improvement is possible. Also the current cameras have such slow readouts that for efficiency, the number of dithers and exposures is typically limited to 2-4. As CMOS advance, readouts can improve the observing duty cycle efficiency by ~ 1.5. Also it is plausible to gain of almost another factor of ~ 2 in efficiency with a zero read noise nearly 100% QE device. Therefore, even in the visible, gains can be made such that observations that benefit from a higher efficiency read outs, a 6 arc min × 6 arc min FOV (versus 3 × 3), zero-read-noise, and improved OTA reflectivity, the net gain will be 1.5 x 4 x 2 x 1.1 = 13!

All in all then significant advances can be made in the UV-Vis such that a 2.4 m telescope with modern detectors and coating will be a significant advance of HST even if it is not commensurate with our dreams of a 8 m or 16 m class UV-VIS mission.

Bottom line: Put significant funding into technology development to bring the key new detectors and coatings to at least TRL6, and we can then have a wonderful mission However, arguing for a new start without these improvements in hand will likely lead to either a new start being declined, or if accepted, not having the technology in hand such that a premature new start will likely lead to huge cost overruns.

2 Some Science Drivers

In order to keep this document short we simply enumerate some science drivers. As noted above see Ulmer, 2009, Proc SPIE, 7222, 33 for details:

2.1 Mainly UV

1. A study of the hot intracluster medium of rich clusters of galaxies: The concept is to use background QSOs along the line of sight to clusters to search for absorption lines due to gas as intermediate temperatures of about 10^5K to 10^6K. This gas *ought to be detectable* and detections will give us a link to the overall missing baryon question. However $\sim 50-100$ sight lines are needed to be assured of detections, and the necessity of about 50-100 targets then requires the increased sensitivity of the NG-SUVO.
2. He II absorption and the ionization history of the Universe out to z of 4.
3. Observing metals in intergalactic filaments
4. Observing the warm hot intergalactic medium (WHIM) and the relationship between galactic winds and metal enrichment of the WHIM.
5. Detecting metals in planetary disks leading toward an understanding the relationship between the metallicity in proto-planetary disks and planet formation.
6. Detecting the water absorption and perhaps even DNA-protein-like absorption features in the atmospheres of extra-solar planets (or extra-solar moons such as Europa or Enceladus).
7. Imaging aurorae on solar system planets, e.g. Jupiter

2.2 Mainly The Visible Band

1. Weak lensing mapping of Dark Matter.
2. Weak Lensing as a probe of the nature of Dark Energy.
3. Larger Deeper GOODs and UDFs (also UV as well).
4. With a coronagraph, imaging of planets (also in the UV as well).
5. Extending the catalog of Legacy images of nearby galaxies.

SPECtroscopic TeRAhertz Satellite “SPECTRAS”

Paul F. Goldsmith[1], William D. Langer[1], Jorge L. Pineda[1] and Dariusz C. Lis[2,3]
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA
[2]LERMA, Paris (France) and [3]California Institute of Technology, Pasadena CA

paul.f.goldsmith@jpl.nasa.gov

The enormous success of Herschel has made it clear that the Terahertz frequency range (corresponding to submillimeter wavelengths) offers vastly powerful probes of astrophysical and planetary processes. Some of the most interesting and surprising results have emerged in the area of high-resolution spectroscopic study of the solar system objects, protoplanetary and protostellar disks, and the interstellar medium of the Milky Way, and nearby galaxies. The Probe concept described here, which builds on the discoveries made by Herschel, is exceptionally broad in its scientific reach, addressing critical questions from the origin of the Earth’s water to the dependence of star formation rate on the properties of galaxies.

A critical underpinning of the SPECTRAS concept is that for velocity-resolved studies of objects ranging from solar system comets to nearby galaxies, the telescope emission is unimportant compared to the quantum noise of heterodyne systems. Consequently, there is little advantage in cooling the telescope optics, in contrast to the situation for photometry and low-resolution spectroscopy. Thus, available funds can be focused on obtaining the maximum aperture size, without worrying about complex thermal shielding and cryogenic systems for keeping the telescope at 5 K – 10 K, as is being contemplated for a number of missions focusing on low-spectral resolution observations.

SPECTRAS is envisioned to be a 6-m class observatory, operating in the frequency range from 500 GHz to 3000 GHz (wavelengths from 0.6 mm to 0.1 mm). The angular resolution, ranging from ~25” down to 4” at the high-frequency end is critical for resolving structure in galaxies, in particular distinguishing spiral arm and inter-arm regions in such tracers as the ionized carbon fine structure line, [CII] 158 μm. SPECTRAS sensitivity will be a factor ~4 greater than that of Herschel in terms of collecting area, but the mapping speed will be dramatically increased by improvements in receiver sensitivity (by factor ~2-3 times better than HIFI), as well as employing large focal plane array receivers, which have been developed for balloon and airborne (SOFIA) use. With a 64-pixel array for the most important bands, the pixels per unit time mapping rate will be increased by a factor of 256 and the areal mapping speed by a factor of 64 relative to Herschel/HIFI.

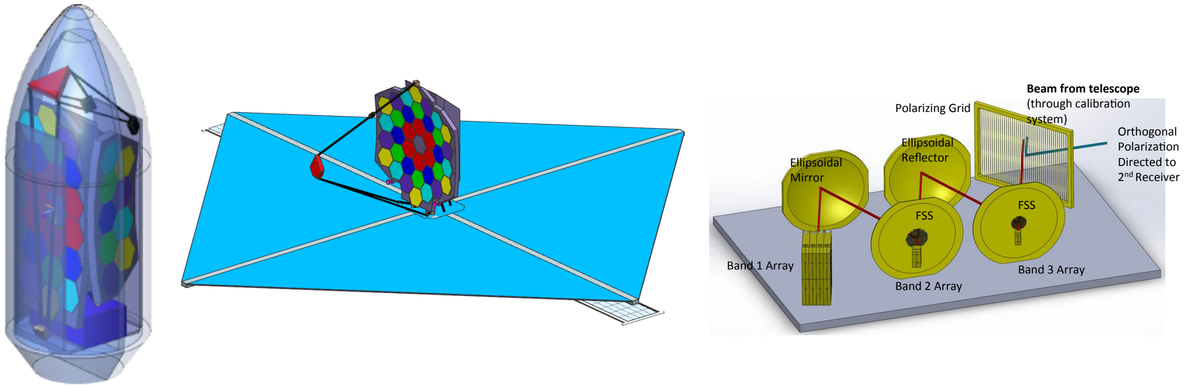
SPECTRAS will target the most important low-lying transitions of both HDO and other isotopologues of water, enabling accurate measurements of the D/H and oxygen isotopic ratios in a large number (on the order of 20) of comets. This measurement has been highlighted to be of prime interest to planetary science, as it can determine whether the Earth’s water came from comets. The limited set of Herschel HIFI measurements of HDO [1], [2] and in-situ measurements [3] suggest significant variations among comets, indicating that the only way to make progress is to measure a statistically significant sample. Water is also an exceptionally important astronomical molecule; its unique astrobiological role is supplemented by its being a critical coolant of the gas phase in star-forming regions. SWAS, Odin, and Herschel have studied water in a variety of astronomical and planetary regions. HIFI observations showed water to be a uniquely powerful tracer of the collapse of dense star-forming cores [4]. Extending this work with significantly higher angular resolution and sensitivity will enable determination of the full three-dimensional velocity field in star-forming cores. The result would be a major, fundamental advance in understanding how stars and planets form. Herschel detected water only in a single protostellar disk (TW Hydrae [5]), having a line width of only 1.5 km/s. With SPECTRAS’s higher sensitivity it will possible to survey many nearby disks and determine their gas-phase water content. Water is the second strongest molecular line emitter in nearby galaxies [6], but only with increased sensitivity, mapping speed and angular resolution can we use it to probe the physics and chemistry of star-forming regions in galaxies of different types. All of this work is impossible from SOFIA and almost so from a balloon.

Atomic fine structure lines are valuable probes of the interstellar medium and star formation. [CII] is the most important coolant of diffuse clouds and as such plays a key role in the atomic-to-molecular transition, which likely governs the rate of star formation. Observations of its 158 µm line directly measure the cooling rate, but high velocity resolution is essential to resolve kinematic structure and avoid problems with foreground absorption. [CII] 158 µm observations have allowed the first detailed look at the "CO Dark Molecular Gas", that adds about 30% to the molecular mass of the Milky Way [7], and have shown how this line traces star formation [8]. The spectral and angular resolution together with the mapping capability of SPECTRAS are essential to extend this study to a large sample of galaxies.

The SPECTRAS design is derived from JWST; as shown in the figure, it incorporates a deployable primary reflector having two folds with 36 hexagonal segments. A deployable tripod supports the hyperbolic secondary reflector. As a result of the ~100X longer operating wavelength, the mass and cost of the telescope are drastically less than JWST. A Falcon 9 Heavy can launch the mission mass of < 7000 kg directly to a Lissajous orbit around L2. A LEOstar-3 bus with upgraded dual star trackers will provide the 1" pointing accuracy. The shroud may be able to accommodate a 6.8-m diameter telescope, but more detailed analysis will be required to study the exact packing of telescope and sunshield. A single layer 34-m diameter sunshield is supported by 4 astromasts. Similar to Herschel, the sunshield and L2 orbit yield an extremely stable thermal environment, making the required 8 µm rms surface achievable without the use of exotic materials. The sunshield size needs further optimization, but the ability to point relatively close to the sun is desirable, and is essential for efficient study of comets.

The receiver system will have 5 bands of array receivers incorporating up to 64 pixels each. The receivers will employ SIS or HEB mixers, and the local oscillators will be produced by frequency multiplication from a precision low-frequency source. Similar single pixel systems were used in Herschel HIFI and small arrays in the upGREAT instrument on SOFIA at frequencies up to 4.7 THz (λ = 63 µm). The frontend components will be cooled by commercial 4 K closed cycle cryocooler. With no liquid cryogen, a minimum lifetime of 5 years can be expected. Spectral lines in multiple bands can be observed simultaneously if desired, as the different bands will be multiplexed using frequency selective surfaces. Dramatic advances in CMOS ASIC devices mean that a single chip 8192 channel digital FFT spectrometer covering 3 GHz bandwidth (450 km/s coverage and 0.06 km/s velocity resolution at the [CII] 1.9 THz line) and consuming only 200 mW (including digitizer, spectrometer, and memory) can serve as the full backend for each pixel.

A slightly different version of SPECTRAS was studied by Team-X at JPL, and the cost estimated to be $1.4B. This was based on conservative telescope design parameters and can likely be significantly reduced.



(Left) Stowed SPECTRAS configuration in Falcon 9 launch fairing; (Center) Deployed configuration (the solar panels on opposite side of sunshade are just visible at two corners); (Right) Multiband reimaging optics, frequency selective surfaces, and focal plane arrays for 3 bands, expandable to 5.

[1] Hartogh, P. et al. 2011, Nature, 478, 218. [2] Lis, D., et al. 2013, ApJ Letters, 774, L3. [3] Lee, S. et al. 2015, Proc. 46th Lunar & Plan. Sci. Conf., 1832, 2716. [4] Keto, E., Caselli, P., and Rawlings, J. 2015, MNRAS, 446, 3731. [5] Hogerheijde, M. et al. 2011, Science, 334, 338. [6] Yang, C. et al. 2013, ApJ Letters, 771, L24. [7] Pineda, J. et al. 2013, A&A, 554, A103. [8] Pineda, J., Langer, W., & Goldsmith, P. 2014, A&A, 570, A121.