Cosmic Origins Program Analysis Group (COPAG) Report to Paul Hertz Regarding Large Mission Concepts to Study for the 2020 Decadal Survey

October 2, 2015

COPAG Executive Committee, on behalf of the COPAG and Cosmic Origins Community:

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Table of Contents

Joint PAG Executive Summary

This is a joint summary of the reports from the three Astrophysics Program Analysis Groups (PAGs) in response to the charge given to the PAG Executive Committees by the Astrophysics Division Director, Paul Hertz, in the white paper "Planning for the 2020 Decadal Survey", issued January 4, 2015. This joint executive summary is common to all three PAG reports, and contains points of consensus across all three PAGs, achieved through extensive discussion and vetting within and between our respective communities. Additional information and findings specific to the individual PAG activities related to this charge are reported separately in the remainder of the individual reports. These additional findings are not necessarily in contradiction to material in the other reports, but rather generally focus on findings specific to the individual PAGs.

The PAGs concur that all four large mission concepts identified in the white paper as candidates for mission concept maturation prior to the 2020 Decadal Survey should be studied in detail. These include the Far-IR Surveyor, the Habitable-Exoplanet Imaging Mission, the UV/Optical/IR Surveyor, and the X-ray Surveyor. Other flagship mission concepts were considered, but none achieved sufficiently broad community support to be elevated to the level of these four primary candidate missions.

This finding is predicated upon assumptions outlined in the white paper and subsequent charge, namely that 1) major development of future large flagship missions under consideration are to follow the implementation phases of JWST and WFIRST; 2) NASA will partner with the European Space Agency on its L3 Gravitational Wave Surveyor, participate in preparatory studies leading to this observatory, and conduct the necessary technology development and other activities leading to the L3 mission, including preparations that will be needed for the 2020 decadal review; and 3) that the Inflation Probe be classified as a probe-class mission to be developed according to the technology and mission planning recommendations in the 2010 Decadal Survey report. The Physics of the Cosmos PAG (PhysPAG) sought input on the mission size category for this mission and finds that it is appropriately classified as a probe-class mission. If these key assumptions were to change, this PAG finding would need to be re-evaluated in light of the changes.

The PAGs find that there is strong community support for the second phase of this activity - maturation of the four proposed mission concept studies. The PAGs believe that these concept studies should be conducted by scientists and technical experts assigned to Science and Technology Definition Teams (STDTs). The PAGs find that the community is concerned about the composition of these STDTs and that there is strong consensus that all of the STDTs contain broad and interdisciplinary representation of the science community. The PAGs also find that the community expects cross-STDT cooperation and exchange of information whenever possible to facilitate the sharing of expertise, especially in the case of the UVOIR Surveyor and the Habitable-Exoplanet Imaging Mission, which share some science goals and technological needs. The PAGs concur that a free and open process should be used to competitively select the STDTs.

Finally, the PAGs find that there is community support for a line of probe-class missions within the Astrophysics Division mission portfolio. The PAGs would be willing to collect further input on probe missions from the community as a following strategic planning charge if asked to do so by the Astrophysics Division Director.

COPAG Executive Summary

The Cosmic Origins Program Analysis Group (COPAG) responded to the flagship mission charge by soliciting broad community input on the flagship mission candidates in an open and inclusive manner. All community input was considered, and our analysis, findings, and some additional considerations are presented in this report. The COPAG finds:

1. The four candidate mission concepts identified by the Astrophysics Division Director, and only these four, are the correct ones for NASA to mature for consideration in the 2020 Decadal Survey. (Joint PAG finding)
2. A Far-IR Surveyor based upon a large, cold, filled-aperture telescope has broad community support, delivers significant increases in sensitivity, spatial resolution, and wavelength coverage over present-day and planned observatories, and is well-suited to addressing key Cosmic Origins science questions envisioned for the 2020s and 2030s.
3. To ensure broad support for the UVOIR Surveyor and the Habitable Exoplanet Imaging Mission within both the Exoplanet and Cosmic Origins communities, significant science capabilities in both topical areas must be baselined for these missions.
4. A flagship mission offering high spatial resolution, high sensitivity, and access to the full range of wavelengths covered by HST (91.2 nm – 2 μm) is essential to advancing key Cosmic Origins science goals in the 2020s and 2030s. Improvement in sensitivity at ultraviolet wavelengths between 91.2 and 110 nm is highly desirable.
5. An X-ray Surveyor having significant imaging and spectroscopic capabilities beyond those planned for the ESA Athena mission has science drivers that are highly synergistic with Cosmic Origins science questions envisioned for the 2020s and 2030s
6. Synergies between the needs of the science community and the capabilities of the human space flight program may provide a path for enabling future flagships to be assembled in space and/or have operating lifetimes significantly longer than 5-10 years through servicing or upgrade activities.
7. There is strong community support for the second phase of this activity – maturation of the four proposed mission concept studies by STDTs competitively selected through a free and open process. (Joint PAG finding)
8. There is no compelling reason to set up an independent review team outside of the STDTs to assess the scientific integrity of the STDTs' Cosmic Origins science assumptions or technical requirements, as is being recommended by the ExoPAG for the characterization of Earth-like exoplanets.
9. There is community support for a line of (probe-class) astrophysics missions that would bridge the mission capability gap between explorers and flagships. (Joint PAG finding)

1. Introduction

In January 2015, the Astrophysics Division Director, Dr. Paul Hertz, charged the Program Analysis Groups (PAGs) with soliciting community input on several candidate flagship mission concepts to mature in preparation for the 2020 Astrophysics Decadal Survey.[1] Dr. Hertz identified a small set of candidate large mission concepts to be studied sufficiently to provide appropriate information for the consideration of the 2020 Decadal Survey Committee. The members of the small set, which were drawn from the 2010 Decadal Survey (*New Worlds, New Horizons in Astronomy and Astrophysics*[2]) and the NASA Astrophysics Visionary Roadmap (*Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades*[3]) follow in alphabetical order, as listed in the white paper:†

- **Far IR Surveyor** – The Visionary Roadmap identifies a Far IR Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.
- **Habitable-Exoplanet Imaging Mission** – The 2010 Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 decadal survey.
- **UV/Optical/IR Surveyor** –The Visionary Roadmap identifies a UV/Optical/IR Surveyor with improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution, and/or wavelength coverage. The 2010 Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 decadal survey.
- **X-ray Surveyor** – The Visionary Roadmap identifies an X-ray Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.

The charge given to the PAGs included soliciting and analyzing community input on the candidate mission concepts, adding or modifying the set of candidate missions, and reporting findings in writing to the NAC Astrophysics Subcommittee prior to its Fall 2015 meeting. The charge is excerpted from the white paper and is included in its entirety in Appendix A for easy reference.

2. Solicitation of Input and Community Engagement

The Cosmic Origins Program Analysis Group (COPAG) solicited broad community input on the flagship mission candidates in an open and inclusive manner, including a series of face-to-face meetings, a pair of virtual (electronic) town halls, a set of workshops, a call for community white papers,[4] and informal discussions over the past 9 months. All of that community input was considered and is reflected in this report. The COPAG community engagement activities, which are listed in Table 1, are described in more detail in Appendix B. Information related to all of these activities is posted on the COPAG website.[5] In the following discussions, we refer to white papers submitted by the community by their associated number (WP#x) in Appendix C.

† Note that the use of the term "Surveyor" in the mission concept titles is a generic term given to future flagship missions in the Visionary Roadmap and is not meant to indicate that the mission's primary function is to perform surveys. Note also that the Habitable-Exoplanet Imaging Mission is often referred to in associated documents as "HabEx", while the UV/Optical/IR Surveyor is often referred to as "LUVOIR".

Table 1: COPAG Community Engagement Activities			
Activity	Location	Date (2015)	Participation
AAS Meeting, Joint PAG Session	Seattle	Jan 4-8	~100 attendees
Virtual Town Hall #1	Electronic	March 10	~50 participants
Joint PAG EC Meeting	Baltimore	March 19	PAG EC members
Call for White Papers	Electronic	March-April	38 white papers received
Far-IR Workshop (SIG#1)	Pasadena	June 3-5	>130 attendees + webex
ExoPAG #12 Meeting	Chicago	June 13-14	COPAG EC representation
UV/Optical Workshop (SIG#2)	Greenbelt	June 25-26	~100 attendees + webex
HEAD Meeting	Chicago	July 1	COPAG EC representation
IAU Meeting, Joint PAG Session	Honolulu	August 7	~70 attendees
Virtual Town Hall #2	Electronic	August 20	~50 participants
AIAA Space 2015 PAG Session	Pasadena	August 31	~50 attendees

3. COPAG Analysis and Findings

The field of astronomy is changing rapidly and will surely continue to do so in the coming decades. Many discoveries and new fields of investigation made possible by the Hubble Space Telescope (HST), Spitzer Space Telescope (SST), and Chandra X-ray Observatory (CXO) were not possible to predict prior to the launch of these observatories. The discovery of water and other compounds in exoplanet atmospheres, imaging of protoplanetary disks around other stars, the detection of the highly-ionized intergalactic medium in the low-redshift universe, the mapping of dark matter through gravitational lensing effects, the confirmation of the accelerating universe and existence of dark energy, the dynamic evolution of galaxies and their resulting star formation over cosmic time, and the detection of objects at redshifts approaching the epoch of initial galaxy formation are but a few examples. With JWST extending COR science to greater depths and WFIRST-AFTA opening new COR science opportunities through wide-field imaging, the bar for a future flagship has been set high. Future flagship missions need to be able to adapt to the ever changing COR science landscape.

The COPAG considered community input on the four candidate missions and solicited suggestions for alternative missions to add to this list. We present our analysis below. All four missions are scientifically synergystic with each other and with other facilities expected to be operational in the late 2020s and 2030s (e.g., ALMA, SKA, LSST, and the ELTs). No other mission concepts garnered broad community support (see Appendix D for a brief discussion).

Finding #1: *The COPAG finds that the four candidate mission concepts identified by the Astrophysics Division Director, and only these four, are the correct ones for NASA to mature for consideration in the 2020 Decadal Survey. (Joint PAG finding)*

3.1. The Far-IR Surveyor

The Far-IR Surveyor envisioned in the Astrophysics Visionary Roadmap would enable a broad range of COR science, ranging from investigations of solar system objects to observations of the first stars and galaxies. The far-IR provides a unique window for unraveling star and planet formation, and is invaluable for understanding the evolution of galaxies from the epoch of reionization to the present day. Sensitive imaging and spectroscopy of stellar systems and galaxies in the far-IR would greatly advance understanding of Galactic star formation, the co-evolution of galaxies and black holes, protogalaxies, and large-scale structure. Direct measurement of emission lines of water and other molecules in molecular clouds and young stellar systems would reveal how the presence and distribution of water and organic molecules evolve with time from protoplanetary disks to habitable planets. The Far-IR Surveyor would easily open a new realm of science capabilities beyond those of SST, SOFIA, and Herschel through its enormous gains in sensitivity. By achieving sensitivity factors of at least two orders of magnitude over previous and existing FIR telescopes, this observatory would routinely make discoveries that are not even imaginable at current sensitivity levels - this is the real promise of the Far-IR surveyor. It would also have tremendous pan-chromatic science synergy with JWST and the Atacama Large Millimeter Array (ALMA), as well as significant gains in sensitivity and spatial resolution that are not achievable on the ground.

The COPAG received several white papers describing science applications for a Far-IR Surveyor [WP#2, 5, 8, 9, 10, 12, 13, 22], as well as a community-based science workshop report outlining both the science case and a basic architecture for the mission.[6] A summary of that report is contained in Appendix E. That report baselines a notional mission concept called the Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory (CALISTO), which is a 5 meter class, actively cooled (T~4 K) space telescope operating in the 25-300 μm band (see also WP#10). The rise of heavy elements in the early universe, star formation and black hole growth in dust-obscured galaxies, and a census of forming planetary systems in our region of the Galaxy are among the primary science drivers identified in these white papers.

While not the only mission concept put forward by the community, a large, cold, filled-aperture telescope has broad support. Other architecture possibilities that the community has suggested include a larger (8-16 meter) segmented telescope variation of CALISTO akin to those described for the Habitable Exoplanet Imaging Mission and the UVOIR Surveyor (WP#24), and interferometer concepts such as the Space Infrared Interferometric Telescope (SPIRIT, WP#22). These other forms of the Far-IR Surveyor would provide even higher angular resolution observations than the baseline CALISTO architecture.

The COPAG recently reviewed the technology needs noted in the white papers received and incorporated them into its yearly input into the 2015 COR Program Annual Technology Assessment Report (PATR).[7] This included development of large-format, ultralow noise far-IR detectors, tunable bandwidth array receivers, improved cooling systems, lightweight segmented mirror systems, and far-IR interferometers. The COPAG reported its technology assessment efforts to the Astrophysics Subcommittee at its July 2015 meeting.

Finding #2: *A Far-IR Surveyor based upon a large, cold, filled-aperture telescope has broad community support, delivers significant increases in sensitivity, spatial resolution, and wavelength coverage over present-day and planned observatories, and is well-suited to addressing key Cosmic Origins science questions envisioned for the 2020s and 2030s.*

3.2. The Habitable Exoplanet Characterization Mission and UVOIR Surveyor

The Habitable Exoplanet Imaging Mission and UVOIR Surveyor mission concepts share many of the same exoplanet and COR science goals embodied in the Astrophysics Visionary Roadmap, which describes an 8-16 meter class mission that will directly observe a sizable sample of diverse exoplanets and provide detailed measurements of their atmospheres, as well as make revolutionary advances in mapping the chemical-dynamical evolution of protoplanetary disks, characterizing the archeology of the Milky Way, measuring star-formation histories for all galaxy types, examining the stellar initial mass function over all mass scales, resolving stellar populations, characterizing black hole masses and their environments, measuring the properties of the first stars, and spectroscopically investigating the intergalactic medium and the epoch of reionization. The breadth of science enabled by such a mission is represented in many of the white papers we received [WP#1, 11, 14, 15, 16, 17, 21, 26, 27, 30, 32, 33, 36, 37, 38] as well as in the HDST study report.[8] The benefits of having a well defined Design Reference Mission (DRM) based on these types of science cases is discussed in WP#23.

Throughout this process we heard from COR community members who are excited about supporting a future flagship mission that that will serve the science needs of both the COR and exoplanet science communities. This was discussed extensively at the June 2015 community workshop held by COPAG Science Interest Group #2. A summary of that workshop can be found in Appendix F. The merging of COR and exoplanet science also figures prominently in the recent community-based study "From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy" commissioned by the Association of Universities for Research in Astronomy (AURA).[8] A brief introduction to this report is included in Appendix G.

The majority of the COPAG envisions a single flagship encompassing these two mission concepts, namely a mission that does both exoplanet characterization and COR science well beyond what is currently possible. This mission would clearly build off similar synergies between exoplanet science and general astrophysics as demonstrated by HST and SST and soon to be realized by JWST and WFIRST. The mission is known by many names. It is called the High Definition Space Telescope (HDST),[8] the Advanced Technology Large Aperture Space Telescope (ATLAST,[9] WP#36), the Large UVOIR Surveyor (LUVOIR), and the Evolvable Space Telescope (EST, WP#11, 28) in its larger aperture incarnations; and by HabEx, HabEx2 (WP#34), Life Finder (WP#20), and the Telescope for Habitable Exoplanets and Interstellar / Intergalactic Astronomy (THEIA),[10] among others in smaller aperture incarnations. A novel concept using a rotating synthetic aperture to synthesize very large circular apertures has also been suggested [WP#29]. This is by no means an exhaustive list. Significant community efforts have gone into describing all of these varietals elsewhere, so we do not repeat those descriptions here. Suffice it to say that the next stage of this NASA flagship study will have ample input to draw upon for science requirements and mission architectures. Some of this information, including a notional science traceability matrix, was recently summarized by COPAG SIG#2 in the report of its June 2015 workshop.[11]

The COPAG and ExoPAG have had productive collaborations and discussions regarding these two mission concepts during the past 6 months. To date, the COPAG and ExoPAG have not been able to reconcile their preferences for the two flagship mission concepts sufficiently to merge them into a single concept. The main discriminator of the mission concepts is science capability, setting aside cost as there has not yet been a proper recent costing for any of these mission concepts. The COPAG favors large aperture (8-16 meter) telescopes to increase both light collecting power and the angular resolution at which objects throughout the universe can be observed. The ExoPAG is also in favor of exploring large apertures, but advocates exploring smaller (4-8 meter) apertures as well, since it may be easier to achieve coronagraph light nulling requirements by using unobscured unsegmented apertures, and starshades may be more effective with smaller aperture telescopes. This difference in opinion and desire to study multiple mission concept options is not surprising at this stage of concept development since there are technical challenges as well as scientific needs to be addressed in considering the efficacy of the candidate missions. Both PAGs are in favor of moving forward with the two mission concepts at this point, with the hope that there can yet be cross-PAG consensus on uniting behind a single concept heading into the 2020 Decadal Survey.

Finding #3: *The COPAG and ExoPAG concur that in order to ensure broad support for the UVOIR Surveyor and the Habitable Exoplanet Imaging Mission within both the Exoplanet and Cosmic Origins communities, significant science capabilities in both topical areas must be baselined for these missions.*

The era of extremely large ground-based telescopes (ELTs) with 20-40 meter primary apertures is nearly upon us. These new facilities will take advantage of enormous light-gathering capabilities, adaptive optics, and sophisticated instrumentation to dramatically extend the reach and performance of ground-based telescopes at optical and near-IR wavelengths. In much the same way that HST extends the frontiers of astrophysics in a manner that is both uniquely revolutionary and complementary to 8-10 meter ground-based telescopes today, a future UVOIR flagship mission will need to address science that is complementary to or beyond the reach of the ELTs. The COR community recognizes that these ground-based ELT capabilities, as well as others available with observatories such as the Large Synoptic Survey Telescope (LSST), will exist and is identifying compelling science opportunities that require a large space-based UVOIR observatory. NASA will need to position its astrophysics mission portfolio accordingly, and capitalize upon the unique advantages of locating observatories in space. A flagship-class UVOIR space mission beyond JWST will be required for NASA space science to remain competitive with, and complementary to, ground-based telescopes at optical/IR wavelengths in the 2020s and 2030s.

We received many comments regarding the technological needs and basic telescope parameters for this mission(s). Some of these are documented in the white papers, studies, and references noted above. Specific science capabilities that are of high priority for the COR community include access to ultraviolet wavelengths below 200nm, preferably down to the rest-frame Lyman-limit cutoff at 91.2 nm to increase the availability of important gas diagnostics [WP#1, 13, 14, 15, 16, 25, 36, 37] and high spatial resolution at all wavelengths to resolve stellar populations, star-forming regions, circumstellar environments, and galaxy fields [WP#14, 15, 16, 21, 27, 30, 32, 33, 38]. Observations at UV wavelengths, particularly those below 200 nm, have specific technology needs, including large-format high quantum efficiency detectors and high reflectivity pan-chromatic mirror coatings. Lightweight ultra-stable segmented mirror systems and high-performance wavefront sensing were also identified as technology needs. These are included in the most recent COPAG input into the preparation of the 2015 COR PATR.[7]

Finding #4: *A flagship mission offering high spatial resolution, high sensitivity, and access to the full range of wavelengths covered by HST (91.2 nm – 2 μm) is essential to advancing key Cosmic Origins science goals in the 2020s and 2030s. Improvement in sensitivity at ultraviolet wavelengths between 91.2 and 110 nm is highly desirable.*

3.3. The X-ray Surveyor

The X-ray Surveyor received less analysis by the COPAG than the three other candidate flagship missions. This was not for lack of support by the COPAG, but rather because the COR community relies predominantly upon observations at UV/O/IR/FIR wavelengths rather than X-ray wavelengths. Community input for this mission is better assessed by the PhysPAG in light of U.S. participation in the ESA-led Athena mission, which is planned to launch in the late 2020s. The X-ray Surveyor concepts being considered would provide much higher angular resolution and soft X-ray spectroscopic capabilities that Athena is not expected to have.

Many of the science investigations outlined in the Astrophysics Visionary Roadmap for the X-ray Surveyor have significant science synergies with the UVOIR and Far-IR Surveyors. This includes the characterization of black holes, accretion disks, astrophysical jets, supernovae, stellar remnants, dark energy, and dark matter. The COPAG finds that there would be strong synergy between the science enabled by an X-ray Surveyor and COR science occurring at other wavelengths, much as there is now with CXO complementing HST and SST, and vice versa. Of course, an X-ray Surveyor would also conduct science for which it is uniquely capable, as described in the Astrophysics Visionary Roadmap. This is recognized as being compelling in its own right.

Finding #5: An *X-ray Surveyor having significant imaging and spectroscopic capabilities beyond those planned for the ESA Athena mission has science drivers that are highly synergistic with Cosmic Origins science questions envisioned for the 2020s and 2030s*

3.4. Telescope Architectures and Servicing

We had numerous conversations with the community and received several white papers describing novel telescope architectures for the missions. Of specific note are those that describe architectures involving evolving segmented primary mirrors [WP#6, 11, 24, 28], which can be increased in size by adding additional mirror segments over a period of time. While suggested as a means for spreading capital investment costs over many years, the design ultimately provides the light collecting power required by the Habitable Exoplanet Imaging Mission, the UVOIR Surveyor, or the Far-IR Surveyor. The initial stage of construction equips the observatory with an assembly of segments that is sufficient to accomplish selected high priority science observations early in the mission lifetime. Succeeding stages build upon the initial architecture at several year increments (nominally 3 – 5 years between launches) and add additional mirrors, structures, and instruments to the telescope to increase its scientific capabilities. This approach can be implemented for any of the normal incidence ultraviolet through far-IR mission concepts in the NASA study call.

The subject of observatory serviceability also arose during many of our community discussions. While clearly necessary for evolvable telescope designs, there is also interest in building off of HST's highly successful servicing legacy to increase science capability and productivity for the next flagship mission, regardless of the architecture chosen for the primary mirror [see, e.g., WP#14, 15, 36]. Treating future flagships as long-lived observatories whose primary infrastructure can be repaired and improved over many years, perhaps even decades, rather than limited life entities (as is the case, for example, with JWST), has broad support and would certainly provide long-term stability for the evolving needs of the COR science community. We note that the FY2009 NASA Authorization Act [Sec. 502. Provision for Future Servicing of Observatory-Class Scientific Spacecraft] states: "The Administrator shall take all necessary steps to ensure that provision is made in the design and construction of all future observatory-class scientific spacecraft intended to be deployed in Earth orbit or at a Lagrangian point in space for robotic or human servicing and repair to the extent practicable and appropriate."

Finding #6: *Synergies between the needs of the science community and the capabilities of the human space flight program may provide a path for enabling future flagships to be assembled in space and/or have operating lifetimes significantly longer than 5-10 years through servicing or upgrade activities.*

3.5. Science and Technology Definition Teams

We had numerous discussions about the formation and composition of the Science and Technology Definition Teams (STDTs) that will be responsible for the next phase of this flagship mission charge. Despite a wide range of opinions on how the STDTs should be structured, there is strong consensus that the STDTs contain broad and interdisciplinary representation of the science and technology communities. The COR community understands that the detailed structuring and composition of the STDTs is NASA's responsibility, as emphasized by the Astrophysics Division Director during plenary PAG sessions with the community.

Finding #7: *There is strong community support for the second phase of this activity – maturation of the four proposed mission concept studies by STDTs competitively selected through a free and open process. (Joint PAG finding)*

The community expects cross-STDT cooperation and exchange of information whenever possible. Similar observatory architectures may be applicable to two, or even three, of the candidate mission concepts. We encourage each STDT to consider the science drivers and the technology tall poles associated with filled apertures of various sizes, paying close attention to the work of the other STDTs that will be looking at similar telescope architectures and sizes. In particular, it may be beneficial for the STDTs formed for the Habitable Exoplanet Imaging Mission, the UVOIR Surveyor, and the Far-IR Surveyor to share their initial thoughts and findings on basic telescope architectures early in the STDT process to reduce duplication of efforts at later stages. Sharing information with industry early in the process would likely elucidate the tall poles and applicability of architecture choices for more than one mission concept.

The ExoPAG is recommending that an independent team outside the STDTs evaluate the science yield and technical readiness of the Habitable Exoplanet Explorer and UVOIR Surveyor mission designs. The COR community has much less stringent requirements for light nulling capabilities than the exoplanet characterization requirements, which are the driving factor for the ExoPAG's proposal of a review team. The COR science community has articulated its needs, with experts in many areas contributing to information available in the white papers listed in Appendix C, concept study documents, workshop proceedings, and peer-reviewed literature. In most cases, these needs can be derived in a very straight-forward manner using known, and widely accepted, results.

Finding #8: *We find that there is no compelling reason to set up an independent review team outside of the STDTs to assess the scientific integrity of the STDTs' Cosmic Origins science assumptions or technical requirements, as is being recommended by the ExoPAG for the characterization of Earth-like exoplanets.*

All community input collected by the COPAG is available online to support the STDT activities. We encourage the STDTs to tap into this rich set of information so as to minimize duplication of effort. The COPAG is willing to facilitate community engagement during the STDT process if asked to do so by NASA.

3.6. Probe Missions

The subject of probe-class missions arose frequently during our discussions of flagship missions with the community. There is broad support for a line of astrophysics missions that would bridge the mission capability gap between explorers and flagships, akin to Discovery-class missions in the Planetary Sciences Division. While we received only few white papers specifying the need for probes (WP#3, 19, 25, 31, 34), past proposal pressure for the Origins Probes and comments from the community indicate that there are many potential science cases for such missions. The community understands that within a cost-capped Astrophysics Division portfolio it would likely be necessary to trade probe opportunities (at a cadence of about once per decade) against other mission opportunities.

We received a wide range of opinions on how probe mission concepts should be developed and whether a charge similar to the flagship mission charge should be issued. In the end, there was no clear consensus on either point. Suggestions for how NASA should proceed included: 1) issuing a probe concept study call for proposals similar to the Origins Probe call for proposals issued in the mid-2000s; 2) supporting a concept development effort akin to that currently envisioned for flagships, although it is unclear how best to limit the number of concepts to be studied since there are many more probe mission concepts than there are viable flagship concepts; 3) doing nothing, with the expectation that the community will either provide input to the Decadal Survey on an individual mission concept basis or will self-organize in some manner to provide coordinated input; and 4) forming a cross-PAG science analysis group (SAG) to develop a community-based case for a probe line as input to the Decadal Survey. Of these, *the COPAG EC favors the development of a cross-PAG SAG to discuss the merits of a probe mission line and to coordinate general community input to the Decadal Survey if appropriate.*

Finding #9: *There is community support for a line of (probe-class) astrophysics missions that would bridge the mission capability gap between explorers and flagships.* (Joint PAG finding)

4. Additional Considerations

We list here some additional considerations that readers of this report may find useful and contain information the COPAG believes should be communicated based upon the community input received.

4.1. Engaging Industry

It is important to get industry involved early in the consideration and discussion of flagship missions, prior to the full definition of detailed mission requirements. Industry has a wealth of information and expertise that NASA and the astrophysics community either do not know exist or do not have the skill sets to utilize. There have been huge industrial investments in hardware, software, and people by other government agencies that are directly relevant to the needs of NASA and the astrophysics community. Tapping into those investments offers the possibility of accelerating the realization of technologies needed for future NASA flagship missions. We heard repeatedly throughout this process that there is a sense that industry involvement in NASA astrophysics missions is dwindling and that expertise may not be available when it is needed for future flagship missions because industry is moving on to other funded activities.

NASA's traditional way to engage industry is to fund industry efforts in parallel with, but separately from, the STDTs and then direct industry to interact with the STDTs, as was the case for JWST, TPF-C, and CXO, for example. This is done primarily to prevent conflict of interest issues that might exclude companies from bidding on future missions. (Federal acquisition regulations make it clear that if a company helps define requirements for a project that the company cannot bid on the effort because of a conflict of interest.) The issue arises because STDTs and other study group charters usually state that they are setting "requirements", even though at early stages in the process these are often very high-level, non-specific needs (rather than requirements) that are usually self-evident to all future work bidders. For example, needing a large aperture primary mirror to increase light collecting power is more an approach to realizing future flagship mission potential than it is a well-defined "requirement", at least at early stages in the development of a mission concept. Cost-effective leveraging of industry participation can occur if the science and engineering needs are shared early enough (e.g., during the STDT process) to provide industry opportunities to respond to these needs with candidate implementations at the appropriate systems, subsystems, and/or component levels.

We encourage NASA to consider finding ways to engage industry at early stages in the development of the four flagship mission concepts in order to tap into the expertise and resources that exist within this sector. This would provide better understanding of mission technical/engineering challenges, and would make it more likely that industry would be proactive in communicating and harvesting relevant existing technologies from other programs for the eventual development of the next flagship mission.

4.2. Costs

All four candidate mission concepts suggested by the Astrophysics Division Director are properly classified as flagships. The subject of flagship missions costs arose during many of the conversations we had with the community. The COPAG EC and chair actively sought to remove, or limit, cost considerations from these community discussions to the extent possible, noting that the current plan calls for the STDTs to develop mission concepts with DRMs that will be iteratively costed by an external party in a consistent manner. Omission of cost considerations occasionally became a point of contention, but in the end we believe it yielded a better, more positive, more science-focused set of findings.

4.3. Community and Cross-PAG Engagement

The process used to engage the science community and collect input was considerably longer than we anticipated would have been necessary given the fairly simple charge given to the PAGs. However, we found the process to be just as important, if not more so, than the actual result. Excellent discussions and interactions with the community developed broader community support and deeper cross-PAG understanding of the community's needs than might have been possible if a shorter timeline had been imposed on the process. Cross-PAG working relationships were improved considerably as a result. *We encourage NASA, the Astrophysics Subcommittee, and the PAG ECs to foster cross-PAG collaborations whenever possible.*

In future activities of this type, it would be useful to find more proactive ways of engaging the international science community, particularly if NASA expects substantial foreign involvement in the resulting mission(s) or activity.

5. This Report

The PAGs discussed and coordinated the production and content of their reports. They decided to issue individual reports rather than a single joint report with individual PAG contributions. However, each PAG report contains an identical Joint Executive Summary that summarizes points of consensus. A copy of that Joint Executive Summary appears at the beginning of this document.

This report was drafted by the COPAG chair in consultation with the COPAG EC, and is based upon community input received by the COPAG in response to the January 4, 2015 flagship mission charge issued by the Astrophysics Division Director. A draft of the report was posted for public comment on September 14, 2015 for two weeks. Authorship was offered to all members of the community who wished to be included. Those who requested authorship acknowledgement are included in the community author list. A final version of this report will be posted to the COPAG website and the astro-ph e-print paper archive after it is presented to the Astrophysics Subcommittee at its October 2015 meeting.

Acknowledgments

We thank the members of the astronomical community, government centers, and industry who have shared their comments, concerns, and expertise about flagship missions during the past nine months. Their input is what made this report possible. We also thank the members of the PhysPAG and ExoPAG ECs who worked closely with the COPAG EC throughout this process, particularly Alan Boss, Scott Gaudi, Mark Bautz, and Jamie Bock. The COPAG EC appreciates the willingness of the other PAGs to share information and to freely discuss community input in an open and collegial manner.

We thank Paul Hertz for providing guidance throughout this process, and for giving the community a chance to prepare for the next Decadal Survey in a fair, structured manner. We are also appreciative of the time he spent with the PAGs during plenary sessions at public meetings, during lunch sessions with the COPAG EC, and on telecons with the PAG chairs.

Finally, we thank our Cosmic Origins Program Officers, Drs. Susan Neff and Deborah Padgett, and our NASA HQ Cosmic Origins Program Scientists, Drs. Mario Perez, Michael Garcia, and Kartik Sheth, for their expert advice, logistical coordination of PAG activities, and ongoing COPAG activity support. We also acknowledge Dr. Ann Hornschemeier for her skillful moderation of several PAG plenary sessions.

References / Electronic Links

[1] Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper

http://science.nasa.gov/media/medialibrary/2015/08/10/White_Paper-Planning_for_the_2020_Decadal_Survey-signed.pdf

[2] New Worlds, New Horizons in Astronomy & Astrophysics
http://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

[3] Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades
http://science.nasa.gov/media/medialibrary/2013/12/20/secure-Astrophysics_Roadmap_2013.pdf

[4] Cosmic Origins Program Analysis Group Call for White Papers
http://cor.gsfc.nasa.gov/copag/rfi/Large_missions_white_paper_solicitation-01Mar2015.pdf

[5] Cosmic Origins Program Analysis Group Website
http://cor.gsfc.nasa.gov/copag/

[6] Far-IR Workshop, June 23-25, 2015 (SIG#1)
http://conference.ipac.caltech.edu/firsurveyor

[7] Cosmic Origins Program Annual Technology Report and Information
http://cor.gsfc.nasa.gov/technology/

[8] From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy (AURA study)
http://www.hdstvision.org/

[9] The Advanced Large Aperture Space Telescope
http://www.stsci.edu/atlast

[10] THEIA: Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy
http://adsabs.harvard.edu/abs/2009AAS...21345804S

[11] Finding the UV/Visible Path Forward: A Community Workshop to Plan the Future of UV/Visible Space Astrophysics, June 25-26, 2015 (SIG#2)

http://asd.gsfc.nasa.gov/conferences/uvvis/

Appendix A: Astrophysics Division Director Charge to the Astrophysics PAGs

(Excerpted from the Astrophysics Division white paper dated January 4, 2015[1])

Charge to the Astrophysics PAGs regarding Large Mission Concept Studies

January 4, 2015

Background

One of the important tasks of the 2020 Decadal Survey will be to prioritize large missions to follow JWST (the highest priority large mission of the 2000 Decadal Survey) and WFIRST (the highest priority large mission of the 2010 Decadal Survey). To enable this prioritization, NASA will provide information on several candidate large mission concepts for consideration by the 2020 Decadal Survey Committee.

Existing strategic planning documents, including the 2010 Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*, and the NASA Astrophysics visionary roadmap, *Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades*, provide candidate mission concepts for the large missions that will follow JWST and WFIRST. These documents have been developed by the astrophysics community and provide the starting point for planning future missions.

Taking into account current programmatic considerations, NASA has identified a small set of candidate large mission concepts to be studied sufficiently to provide appropriate information for the consideration of the 2020 Decadal Survey Committee. The members of the small set follow, in alphabetical order.

- Far IR Surveyor – The Visionary Roadmap identifies a Far IR Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.
- Habitable-Exoplanet Imaging Mission – The 2010 Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 decadal survey.
- UV/Optical/IR Surveyor –The Visionary Roadmap identifies a UV/Optical/IR Surveyor with improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage. The 2010 Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 decadal survey.
- X-ray Surveyor – The Visionary Roadmap identifies an X-ray Surveyor with improvements in sensitivity, spectroscopy, and angular resolution.

Specific Charge to the Program Analysis Groups

Each of the three Astrophysics Program Analysis Groups (PAGs) – the Cosmic Origins Program Analysis Group (COPAG), the Exoplanet Exploration Program Analysis Group (ExoPAG), and the Physics of the Cosmos Program Analysis Group (PhysPAG) – are charged with reviewing this small set of candidate large mission concepts and suggesting additions, subtractions, and other useful commentary. The results of this review shall be reported to the NAC Astrophysics Subcommittee in the form of a report.

In particular,

1. Each PAG, under the leadership of its Executive Committee, shall broadly solicit the astronomy and astrophysics community for input to the report in an open and inclusive manner. To accomplish this, each PAG is empowered to envision and use its own process.
2. Each PAG shall keep the number of large mission concepts in the set as small as possible; PAGs are specifically charged to consider modifications and subtractions from the small set, and not just additions.
3. Each PAG shall produce a report, where it shall comment on all large mission concepts in its small set of large missions, including those in the initial small set and those added or subtracted. Where there is existing analysis to support it, PAGs are encouraged to comment on the cost range anticipated for large mission concepts. A suggested template for the report is given below.
4. Each PAG may choose to have one or more face-to-face or virtual meetings or workshops in developing its report; said meetings may be scheduled in proximity to existing community meetings or conferences. Limited funding is anticipated by the Astrophysics Division to support a dedicated face-to-face workshop. The Astrophysics Program Offices will support the PAGs in any logistics required to facilitate these activities.
5. Although there is no page limit for the report, each PAG shall strive to be succinct.
6. Each PAG shall submit its report in writing to the NAC Astrophysics Subcommittee no later than two weeks prior to its Fall 2015 meeting (meeting schedule not yet known).

<u>Suggested Report Format</u>

Every PAG is asked to submit a short report of their analysis to the NAC Astrophysics Subcommittee by the date specified above. While there are no prescriptions for the format of the report (other than being succinct), some guidelines are provided. Each PAG will be free to structure their report as they see fit.

It is suggested that each PAG report include the following:

1. Process followed by the PAG to solicit input from community (meetings, white papers, emails, etc.);
2. Brief description of the community response;
3. Procedure and criteria used for PAG analysis of the community response;
4. Outcome of the analysis and final small set of mission concepts submitted to the NAC Astrophysics Subcommittee; every mission concept that is retained, added, or subtracted must be accompanied by a short rationale; and
5. Any additional considerations for NASA.

Should a PAG wish to provide NASA information regarding potential probe-class missions, to inform any future process for considering probe-class mission studies, such information may be appended to the report.

Appendix B: Solicitation of Community Input and Community Engagement Activities

Activities listed in Table 1 (see Section 2) are described in this Appendix. These activities were announced electronically through the COR email distribution and other electronic means, as well as by word of mouth.

The three PAGs coordinated many of their activities related to the flagship mission charge. This began in earnest with a joint-EC meeting at STScI on March 19, 2015 at which the PAGs discussed their plans for responding to the charge, information that should be shared, and solicitation of community input. A notional set of mission parameters for each mission concept was also developed as a reference for discussions with the community. The meeting set a cooperative tone and solidified further cross-PAG collaboration throughout the process.

The individual PAGs invited members of the other PAG ECs to various workshops, telecons, and meetings they hosted.

Face-to-face meetings with the community were held at major astronomical conferences to maximize participation of the community. These consisted of short presentations on the flagship mission charge, the status of the COPAG Executive Committee's (EC's) activities related to the charge, and question and answer sessions. Some of these community meetings also included a cross-PAG plenary session with an introductory presentation by the Astrophysics Division Director, as well as breakout sessions for ongoing science interest groups (SIGs, see below). In all cases, these meetings were well attended, typically with 50-80 people present for the COPAG-specific gatherings. Virtual participation was also available for many of these sessions.

Members of the COPAG EC held a lunch session with Paul Hertz at the January 2015 AAS meeting to hear his thoughts on the flagship mission charge and his expectations of the PAGs. This proved to be useful in ensuring that the COPAG EC understood his reasons for issuing the charge and for communicating our thoughts on how the community should be engaged in the process.

Two virtual town halls introduced the charge to the community and outlined the COPAG's response to the charge (March 2015), and summarized community input, analysis, and findings (August 2015). Both town halls were approximately two hours in duration. They were well attended, with 50-80 participants per town hall.

The COPAG's Far-IR science interest group (SIG#1) held a workshop on the Caltech campus in June entitled "Far-IR Surveyor Workshop". There were excellent talks about science and technology, along with spirited discussions about what the Far-IR Surveyor should be. There were also multiple science breakouts organized along broad themes: high-redshift/cosmology, star formation in the Milky Way, nearby galaxies, and solar system and planetary science. These sessions were used to pull together the key science questions that a Far-IR Surveyor would address. The organizing committee has issued a report that summarizes the results of the workshop and the key science articulated by the community. It can be found on the workshop website[6] along with the workshop agenda, workshop summary report, participant list, white papers, and presentations. The SIG endorsed the maturation of the Far-IR Surveyor concept.

The COPAG's UV/optical science interest group (SIG#2) held a workshop at the Goddard Space Flight Center in June entitled "Finding the UV/Visible Path Forward: A Community Workshop to Plan the Future of UV/Visible Space Astrophysics". This workshop discussed science drivers and technology needs at ultraviolet and optical wavelengths, and included discussions of cross-discipline uses of future flagships that would characterize exoplanet atmospheres and serve as highly capable all-purpose observatories in much the same way that the HST currently does. There were breakout sessions for the SIG's working groups to delve deeper into specific science and technology areas, as well as time for those working groups to discuss their findings with the other workshop participants. Information about the workshop can be found on the workshop website[7] along with the workshop agenda, workshop summary report, participant list, white papers, and presentations. The SIG endorsed the maturation of the UVOIR Surveyor and Habitable Exoplanet Imaging Mission concepts.

A special joint PAG session was held at the International Astronomical Union meeting in August to present the preliminary findings of the PAGs to the community. This was the first opportunity to do so at a large community meeting. The session included opening remarks by Paul Hertz, a summary of joint PAG findings, descriptions of individual PAG activities, and a question and answer session. The meeting was well attended, with approximately 70 participants. Despite being an international meeting, non-U.S. attendance was modest.

On March 10, 2015 the COPAG issued a call for community white papers to provide input on the four notional flagship missions in the PAG charge. The call solicited community input on the relevance of the candidate missions to key science topics that would need to be addressed by future flagship missions, the technical capabilities that the candidate missions would need, the technologies that would be needed to realize these missions, and the completeness of the candidate mission list. The nominal deadline for white papers was April 24, 2015, but in practice the COPAG accepted several additional white papers through the middle of August. White papers relevant to the PAG charge that were submitted directly to the SIGs for the two workshops described above were also included as input. Thirty-eight white papers were received in addition to the SIG workshop reports. All white papers were made available to the ExoPAG and PhysPAG for their consideration. The white papers [WP], which are numbered and summarized in tabular form in Appendix A, are archived on the COPAG website.

The COPAG EC held bi-weekly telecons to discuss the flagship mission charge, progress in responding to the charge, and community input received. This was the primary topic of conversation at these telecons in the February-August timeframe. On several occasions, the COPAG invited outside experts to provide insight into related activities (e.g., technology development of segmented and monolithic mirrors, background on the Gravitational Wave Mission, and so forth).

The PAG chairs coordinated and presented updates on their activities to the Astrophysics Subcommittee at the Subcommittee meetings in March 2015 and July 2015. The PAG chairs also communicated regularly throughout this process, primarily through email. The PAG chairs held a telecon on July 3, 2015 to discuss the contents of the joint PAG executive summary. During a follow-up joint PAG chair telecon with Paul Hertz on July 13, 2015, the chairs discussed the flagship charge and initial results of the PAG analyses.

Appendix C: White Papers Received From the Community

(See http://cor.gsfc.nasa.gov/copag/rfi/ for electronic versions of these white papers.)

#	Lead	Title	Concept	Size
1	Andersson	Science Cases for Ultraviolet Polarimetry in the 21st Century	HabEx, UVOIR	"large"
2	Appleton	Mapping Turbulent Energy Dissipation through Shocked Molecular Hydrogen in the Universe	FIR	5m+
3	Ardila	Are Flagships the Best Way to Advance Astrophysics?		
4	Ardila	Cubesats for Astrophysics		
5	Armus	The Dusty Co-evolution of Black Holes and Galaxies: A Science Case for a Large Far-IR Space Telescope	FIR	5m+
6	Baldauf	Actuated Carbon Fiber Reinforced Polymer Mirror Development	UVOIR	10-20m
7	Batcheldor	Astrophysics Enabled by Extreme Contrast Ratio Technologies	HabEx, UVOIR	8m
8	Bauer	FIR-Survey of TNOs and Related Bodies	FIR	5m+
9	Bergin	Unlocking the Secrets of Planet Formation with Hydrogen Deuteride	FIR	5m+?
10	Bradford	A Cryogenic Telescope for Far-Infrared Astrophysics: A Vision for NASA in the 2020 Decade	FIR	5m+
11	Breckinridge	Imaging Polarimetry for ExoPlanet Science & Astrophysics	UVOIR	10-20m
12	Casey	Dust in Distant Galaxies - Overcoming Confusion Noise with a 5m FIR Facility	FIR	5m+
13	Cooray	Far-Infrared Spectral Line Studies of the Epoch of Reionization	FIR	5m+
14	Dalcanton	A Joint Exoplanet & UVOIR Surveyor	UVOIR	>8m
15	Ebbets	The Earliest Epoch of Star-formation in the Very Young Universe	HabEx, UVOIR	>4m
16	France	Characterizing the Habitable Zones of Exoplanetary Systems with a Large Ultraviolet/Visible/Near-IR Space Observatory	UVOIR	10m+
17	Gaensicke	The Bulk Composition of Exo-planets	UVOIR	10m
18	Green	Flagship Missions for the Decadal Review		
19	Heap	Galaxy Evolution Spectroscopic Surveyor (GESS)	Probe	1.5m
20	Heap	Life-Finder	HabEx	4m
21	Kalirai	Precision Ages for Milky Way Star Clusters	UVOIR	10m?
22	Leisawitz	Interferometry Concept for the Far-Infrared Surveyor	FIR-Interferometer	1.5m
23	Lightsey	Importance of Design Reference Missions for Developing the Next Large Mission Concepts		
24	Lillie	An Evolvable Space Telescope for the Far Infrared Surveyor Mission	FIR	10-20m
25	Linsky	Exoplanet Environment Monitor	Probe	

26	McCandliss	Definitive Determination of Galaxy Luminosity Functions at Energies Above the Hydrogen Ionization Edge	UVOIR	10-12m
27	Natarajan	Probing Transient Structures in the Universe	UVOIR	10m?
28	Polidan	An Evolvable Space Telescope for Future UV/Opt/IR Astronomical Missions	UVOIR, FIR	10-20m
29	Polidan	A Rotating Synthetic Aperture (RSA) Space Telescope for Future UV/Opt/IR Astronomical Missions	UVOIR, FIR	18m x 3m
30	Rampazzo	UVOIR Surveyor: The Need for High Resolution, Wide Field, Deep Multi-Wavelength Imaging and IFU Spectroscopy	UVOIR	8-10m
31	Rizzo	Probe Class Missions in the Far Infrared	Probe	
32	Roederer	The Origin of the Elements Heavier than Iron	UVOIR	10m?
33	Roederer	The First Stars and the First Metals	UVOIR	10m?
34	Swain	HabX2: A 2020 Mission Concept for Flagship Science at Modest Cost	HabEx	3m
35	Thorpe	Listening to the Cosmic Dawn!	Grav. Wave	
36	Thronson	A Large-Aperture UVOIR Space Telescope	UVOIR	10m+
37	Tumlinson	Galaxy Fueling and Quenching: A Science Case for Future UV MOS Capability	UVOIR	10-12m
38	Williams	UV/Optical/IR Surveyor: The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies	UVOIR	8-10m

Appendix D: Other Missions Considered

D.1. Gravitational Wave Mission

Gravitational wave astronomy will open new avenues of investigation for COR science, as outlined in the Astrophysics Visionary Roadmap. This new means for exploring energetic events and distortions in the space-time continuum will have tremendous synergy with electromagnetic radiation observations designed to understand the origins of gravitational wave events, characterize the properties of their sources, and assess their source environments.

We considered but did not include a future gravitational wave mission in the list of candidate flagship mission concepts to be matured because we are assuming NASA will partner with the European Space Agency (ESA) on its L3 Gravitational Wave Surveyor. We expect that NASA will participate in preparatory studies leading to this observatory, and conduct the necessary technology development and other activities leading to the L3 mission. We received input from the community supporting the evaluation of U.S. participation in the ESA mission, and the associated science definition, costing, and technology development activities [see WP35]. With the upcoming launch of the LISA Pathfinder technology demonstration mission in late 2015 and subsequent definition of the L3 mission, it is important that such assessments be made in time for the U.S. to understand the expected level of science return and appropriate level of participation needed to realize the science return from the resulting mission.

D.2. Cosmic Dawn Mission

Somewhat surprisingly, there was little community discussion with the COPAG about "cosmic dawn", or the period of formation of the first stars, as a driver for a future flagship mission. The challenge of understanding the history of the universe at these early times is outlined in the Astrophysics Visionary Roadmap, with the suggestion that an eventual mission to map the redshifted light given off by the very first stars, black holes, and galaxies may require an ambitious array of radio antennae on the back side of the moon. Perhaps it is a bit early to plan such an investigation, which would surely benefit from precursor observations by JWST and other telescopes. The COPAG's newly-formed Cosmic Dawn Science Interest Group (SIG#3) will be actively engaging the community in the coming years in discussions of the science drivers and technologies needed to eventually address this need.

Appendix E: SIG#1 (Far-Infrared Science and Technology) Workshop Summary

In order to provide input to the NASA Program Analysis Groups as laid out by the Jan. 2015 NASA whitepaper, Planning for the 2020 Decadal Survey, a community workshop was held from 3 to 5 June 2015 in Pasadena, CA to help define the key science drivers and leading architecture for the FIR Surveyor (as put forward in the 2013 NASA Astrophysics Roadmap, *Enduring Quests, Daring Visions*). Approximately 150 members of the far-infrared community from over 40 institutions worldwide attended the workshop either in person or via webex.

The workshop consisted of invited science presentations covering Galactic star formation, protostellar disks, debris disks, astrochemistry, planet formation, nearby galaxies, AGN and starburst galaxies, the early universe, and large-scale structure. In addition there were presentations describing the two leading FIR Surveyor architectures (described below), synergies with other space-borne and ground-based facilities that would be operating in the 2020s, and key far-infrared detector, cryocooler, and telescope technologies. Science breakout groups centered on the solar system and planetary formation, nearby galaxies, the Milky Way and the early universe discussed the key science questions and themes that would drive the requirements for the FIR Surveyor. The summaries from these groups were discussed in plenary sessions at the end of each day. The breakout group summaries and general discussions became integral parts of the workshop report. The workshop overview, as well as presentations and supporting documentation are available online at: http://conference.ipac.caltech.edu/firsurveyor/

Two leading architectures for the FIR Surveyor were identified before the workshop based on a number of FIR community meetings over the past 13 years. These architectures were a direct detection, cryo-cooled double-Fourier interferometer, and a large, wide-field cryo-cooled single-aperture telescope. Both platforms provide the capability for sensitive imaging and spectroscopy in the far-infrared. During the second day of the workshop, a straw poll was conducted of the participating US scientists. A clear majority of respondents favored the large, filled-aperture telescope as the architecture best suited to addressing the science questions deemed most compelling by the workshop participants. The straw-person parameters envisioned for the FIR Surveyor mission include:

- Telescope temperature of < 4K, actively cooled.
- Telescope diameter ~ 5m, potentially off-axis.
- Telescope field of view ~1 degree at 500 microns.
- Total number of detectors is 1-5 x 10^5
- Wavelength coverage of 25-400 microns, with possible extension to ~800 microns.
- Instruments include: wide field, broad-band R~500 imaging spectrometers, high-resolution (R~300,000) spectrometers, and continuum cameras potentially with polarization capability.

Appendix F: SIG#2 (UV/Optical Science and Technology) Workshop Summary

SIG #2 Workshop - Finding the UV-visible Path Forward

NASA GSFC June 25/26, 2015

The SIG held its first workshop to consider a variety of discussion topics that had been under development since the opening meeting in Seattle in January. The workshop was attended by as many as 100 scientists and technologists both in person and online as we continued work performed in the run-up to the meeting. Breakout sessions were held for the four subcommittees in the SIG:

- Next generation UV-visible science
- Enabling technologies for the UV-visible from space
- The range of mission sizes that could enable UV-visible science
- Understanding how Flagship-class missions could benefit UV-visible science

The workshop took time on the second day to discuss the question of Flagship-class missions identified by NASA SMD for further analysis, and whether there was support for those mission concepts. Both the UVOIR Surveyor and the Habitable Exoplanet Imaging Mission were supported by the SIG for additional study using STDTs along with additional recommendations listed below.

- The SIG did not suggest any additions or subtractions to the list of four concept studies.
- The SIG strongly recommended the endorsement and study of both a 10m+ class UVOIR Surveyor and the smaller UV-visible HabEx mission concepts.
- The SIG recognized the potential of the 10+ m UVOIR Surveyor to make compelling discoveries in both cosmic origins and exoplanet science.
- Based on input from the ExoPAG, the SIG assumed that HabEx concept is smaller than the UVOIR Surveyor although the exact HabEx aperture has not yet been determined. The SIG did not explicitly explore the astrophysical science applications of a smaller aperture mission. Although a smaller aperture telescope may address many of the same astrophysical themes, it cannot achieve the sensitivity or resolution that a larger 10+ m telescope will deliver. Even more than its aperture, the suitability of HabEx for cosmic origins applications will depend critically on two yet-to-be defined capabilities: its field of view in the UV/visible and its sensitivity into the far ultraviolet.
- Among the critical UV-visible technologies that need continued investment to be sufficiently mature for consideration by the 2020 Decadal survey are optical coatings, large format radiation-tolerant high efficiency photon-counting detectors, coronagraphs, and the accommodation of coronagraphic instruments in large-scale telescopes via technologies to address dynamics of the structure. It is particularly important to develop coatings and multiplexing detectors/instruments that maximize sensitivity into the far ultraviolet without compromising coronagraphic requirements.
- The SIG believed that a broad spectrum of precursor missions will be necessary to vet the new science, mature the required technologies and establish the credible workforce required to augment the scientific productivity and impact of large Flagships, while controlling risk and cost. These other missions will include not only suborbital and explorer-class facilities,

but also Probe-class spacecraft (cost <$1B), more ambitious than Explorers but more focused than Flagships.

- The SIG also believed there are several compelling opportunities to work with international partners towards Flagship-class missions that fulfill the science goals discussed in the workshop, and encouraged NASA to explore these possibilities. In that regard, the SIG saw a benefit to including ESA, CSA and Asia-based scientists as observers in the STDTs and requested that NASA pursue this possibility.

Appendix G: AURA "From Cosmic Birth to Living Earths" Report on the Need for a High Definition Space Telescope

This report is the culmination of a community-based two-year study on future space-based options for ultraviolet and optical astronomy undertaken by AURA to advance understanding of the origin and evolution of the cosmos and the life within it. The study co-chairs, Professors Julianne Dalcanton (U. Washington) and Sara Seager (MIT), circulated the report electronically to all three PAGs. The report can be can be found in its entirety at http://www.hdstvision.org/. The introduction from that report is reprinted verbatim here.

FROM COSMIC BIRTH TO LIVING EARTHS

Nobel laureate Dr. Riccardo Giacconi predicted in 1997 that in the next century humanity would have the tools to "study the evolution of the Universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA." The time has arrived to accept this challenge.

Astronomical discoveries emerged at a breathtaking pace over the last two decades. We found that the Universe's expansion is accelerating, powered by as-yet-unknown physics. We saw signs of massive black holes lurking at the heart of nearly every large galaxy. We mapped the earliest ripples in the distribution of matter and traced their development through 14 billion years of star formation and galaxy evolution. We identified thousands of planets outside our Solar System, many of them small and rocky, and used them to show that there are at least as many planets as there are stars in the Milky Way Galaxy.

And yet, with all we know, and with all we have achieved, some of humanity's most compelling questions remain unanswered: Are we alone in the Universe? Are other Earth-like worlds common? Do any have signs of life? How did life emerge from a lifeless cosmic beginning? Curious humans have asked these questions for millennia, but for the first time we can foresee building the astronomical technology required to find dozens of Earth-like planets, to search these planets for signs of life, and to tell the cosmic story of how this life came to be. Over the next decade, progress in instrumentation will rise to the challenge of directly imaging faint planets in orbit around nearby stars and of characterizing their atmospheres. Our understanding of the frequency and size distribution of exoplanets has grown in the past five years to the point where it is statistically very likely that we will find Earth analogs orbiting other stars. These technological and scientific advances, combined with the fundamental quest to understand the evolution of the Universe, now provide an opportunity to meet Dr. Giacconi's challenge to connect cosmic birth to living Earths.

To define a vision for meeting this challenge, the Association of Universities for Research in Astronomy (AURA) commissioned a new study of space-based options for ultraviolet (UV) and optical astronomy in the era following the *James Webb Space Telescope*'s mission. This study "FROM COSMIC BIRTH TO LIVING EARTHS" follows AURA's charge to promote excellence in astronomical research by providing community access to state-of-the-art facilities. AURA tasked a team of research astronomers and technologists to "assess future space-based options for UV and optical astronomy that can significantly advance our understanding of the origin and evolution of the cosmos and the life within it."

We conclude, after careful consideration of the science cases and technological approaches, that a 12 meter class space telescope with sufficient stability and the appropriate instrumentation can find and characterize dozens of Earth-like planets and make transformational advances in astrophysics. Beyond purely scientific considerations, a single observatory covering all areas is also likely to be the optimum programmatic choice. This is true even if, under some assumptions, smaller and more focused observatories could address narrower science aims more efficiently. Exoplanet exploration and astrophysics are stronger together.

The broad outlines of this facility are clear and well-motivated. For example, we know with reasonable accuracy the frequency of planets around other stars, and how many are about the right size and temperature to be similar to the Earth. A 12 m class space-based telescope could detect enough of these planets to perform a robust census of habitable worlds and determine their physical and chemical characteristics: Do their atmospheres contain oxygen, water vapor, and other molecular gases characteristic of life? Is there evidence for continents and oceans on their surfaces? Are there detectable seasonal variations in their surface properties? Telling the full story of life in the cosmos will also require us to show how life's ingredients came together from the diffuse remnants of the Big Bang. The galaxies that form stars, the stars that form the heavy elements, and the planets that host life all have a role in this origins story. We find that a telescope designed to observe from UV to near-infrared wavelengths is not only capable of detecting signs of life on nearby worlds, but can also trace the origins of life's galactic home and raw chemical ingredients back to the earliest epochs of the universe. *The concept we propose is called the "High-Definition Space Telescope"* (*HDST*). *HDST will achieve unprecedented angular spatial resolution and sensitivity in the UV and optical and will reach the extreme contrast required to separate Earth-like planets from the glow of their parent stars and search them for signs of life.* Equipped with a versatile instrument package to optimize its scientific yield, *HDST* would be operated as a general observatory supporting a broad range of investigations, while simultaneously seeking the answer to some of our most profound questions.

Appendix H: Acronyms

AIAA	American Institute of Aeronautics and Astronautics
ALMA	Atacama Large Millimeter Array
ATLAST	Advanced Technology Large Aperture Space Telescope (mission concept)
AURA	Association of Universities for Research in Astronomy
CALISTO	Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory
COPAG	Cosmic Origins Program Analysis Group
COR	Cosmic Origins
CXO	Chandra X-ray Observatory
DRM	Design Reference Mission
EC	Executive Committee
ELT	Extremely Large Telescope
ESA	European Space Agency
EST	Evolvable Space Telescope
ExoPAG	Exoplanet Exploration Program Analysis Group
GSFC	Goddard Space Flight Center
HabEx	Habitable Exoplanet Imaging Mission (short form)
HDST	High Definition Space Telescope (mission concept, AURA mission report)
HEAD	High Energy Astrophysics Division (of the American Astronomical Society)
HST	Hubble Space Telescope
IAU	International Astronomical Union
IR	Infrared
JWST	James Webb Space Telescope
LISA	Laser Interferometer Space Antenna (mission concept)
LSST	Large Synoptic Survey Telescope
LUVOIR	Large UV/Optical/IR Mission
NASA	National Aeronautics and Space Administration
PAG	Program Analysis Group
PATR	Program Annual Technology Assessment Report

PhysPAG	Physics of the Cosmos Program Analysis Group
SAG	Science Analysis Group
SIG	Science Interest Group
SKA	Square Kilometer Array
SPIRIT	Space Infrared Interferometric Telescope
SST	Spitzer Space Telescope
STDT	Science and Technology Definition Team
THEIA	Telescope for Habitable Exoplanets and Interstellar / Intergalactic Astronomy
TPF-C	Terrestrial Planet Finder with internal Coronagraph (mission concept)
UV	Ultraviolet
UVOIR	Ultraviolet/Optical/Infrared
WFIRST	Wide Field Infrared Space Telescope
WFIRST-AFTA	Wide Field Infrared Space Telescope equipped with Astrophysics Focused Telescope Assets
WP	White Paper (followed by a # corresponding to the list given in Appendix A)