Hubble's Science Legacy:
Future Optical-Ultraviolet Astronomy from Space

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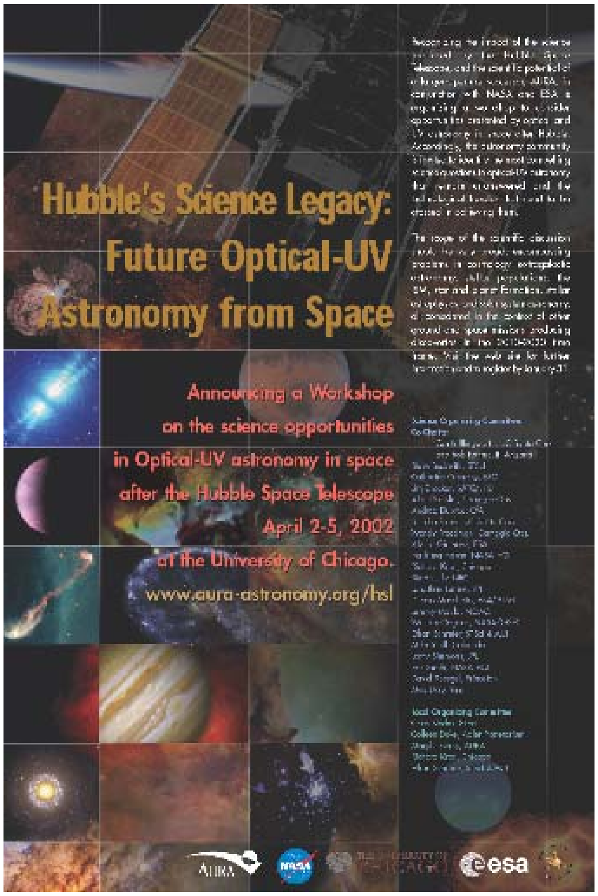

Hubble's Science Legacy: Future Optical-UV Astronomy from Space

Announcing a Workshop on the science opportunities in Optical-UV astronomy in space after the Hubble Space Telescope April 2-5, 2002 at the University of Chicago. www.aura-astronomy.org/hsl

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Executive Summary

The foundations for the *Next-generation Hubble Space Telescope* (NHST) are two workshops that developed the science case for an Optical-UV successor to HST. The 2002 Chicago workshop *Hubble's Science Legacy: Future Optical-Ultraviolet Astronomy from Space* (ASP Conf. Series, Vol. 291, eds. Sembach et al. 2003) built on the science goals and recommendations of the 1998 Boulder workshop *Ultraviolet-Optical Space Astronomy Beyond HST* (ASP Conf. Series, Vol. 199, eds. Morse, Shull, & Kinney 1999). These workshops made an impressive scientific case, highlighting the wide-ranging, forefront science that could be addressed by Optical–UV missions in space. The key science objectives for the next decade include:

1. *Planet detection and characterization* (distribution of planetary orbits and properties; inner planets and earth–like planets)
2. *Star/planet formation* (evolution and dynamics of protoplanetary disks; disk evolution; structural and spectral diagnostics; planetary signatures; synergy with observations at other wavelengths)
3. *Dispersed baryons in the universe* (missing mass and detection of the dominant baryon component in the "cosmic web"; IGM and its interaction with star formation and the ISM in galaxies; structure, ionization, and chemical evolution of the IGM; feedback cycles of star formation, galaxy assembly)
4. *Galaxy formation and evolution* (evolution of structure and stellar populations of distant galaxies as revealed in the redshifted UV, combined with observations of the redshifted optical and infrared with JWST and ALMA; complemented by "archaeology" of nearby galaxies – the time history of galaxy development from stellar population studies)
5. *Central black hole formation and development* (characterizing the role of black hole buildup and AGNs in galaxy formation and evolution; detailed structure and dynamics of the centers of local galaxies, complemented by AGN activity and frequency in low– and high–redshift galaxies)
6. *Cosmological issues* (distance scale, dark energy, and dark matter; improved measurement of the distance scale using Cepheids to much larger distances; the use of lensing to map cosmological geometry; supernovae as "standard candles").

Many imaginative science goals were also identified, ranging broadly from planetary studies in our own solar system, through stellar properties and stellar evolution, to the ISM (in addition to the IGM emphasized above), to globular clusters and nearby galaxy properties. The combination of new discoveries with the more incremental but fundamental advances that have made HST so powerful, clearly exists for NHST.

While the breadth of the scientific potential was very encouraging, focus was also given to what has been called the "killer aps" (Killer Applications) for NHST. This term originates from software developers who look for the applications that make their products a "must buy" for consumers. We face the same problem in "selling" our very expensive missions. What are the science goals that capture the imagination, not just of our colleagues, but also of the public, NASA, agencies responsible for budgeting, and our representatives in government who will ultimately fund the mission?

The direct detection and imaging of planets can obviously be categorized as a "killer ap". Other potentially compelling applications include the mapping of the "cosmic web", star/planet formation, and early galaxy formation/evolution (including the role of black holes). Which of these provides the strongest justification for NHST remains an open question at this stage, but the number of such applications in itself demonstrates the richness of fundamental science that would be produced by such an observatory.

The scientific goals gave rise to a conceptual model for NHST, which could be summarized through its core capabilities. First is the need for at least a factor-of-ten gain over HST, either through increased aperture or, more likely, through gains in detectors, gratings, and wavelength multiplex efficiencies. The capabilities that are unique to optical–UV astronomy in space, and thus are of the highest scientific importance are:

- High–throughput (wavelength-multiplexed) UV spectroscopy
- Wide–field optical diffraction–limited imaging
- High dynamic range optical coronagraphy

Such capabilities can be made more specific by noting that the discovery space for NHST could be characterized as being:

1. UV spectroscopy at least a factor of ten fainter than HST/COS
2. Imaging at least ten times fainter than HST ACS/WFC3
3. Resolution <10 mas (match 2μm adaptive optics on CELT/GSMT)
4. Larger field of view than AO systems; ten times larger than HST/ACS or WFC3.

The 2003 Origins Roadmap identifies Research Area #1 — *"How did the cosmic web of matter organize into the first stars and galaxies?"*. The ISM/IGM program could be accomplished through a specific, modestly-priced mission that could be accommodated within an enlarged Explorer program of order $400–500M using a ∼3–4m class telescope with a UV spectrograph containing detectors of high quantum efficiency (QE) and, perhaps, highly efficient multiplexing in wavelength bands. However, many of the other key science goals required missions that were larger, and more challenging, especially for planet searches. For these, we have identified a number of possible missions, including a ∼4 m coronagraphic telescope that is a TPF precursor (called "TPF–lite" at the workshop), which could eventually lead to an ∼8 m class telescope that is uniquely optical-UV in its science goals. If TPF/Life Finder is ultimately an optical coronagraph and not an IR interferometer, then an ∼8 m TPF could potentially have broader optical–UV science capabilities as well. It is these telescopes, as a phased program, that would be seen as "NHST". Under this scenario, with coupling to the TPF program, NHST could be a program of two or more missions, instead of a particular mission.

A phased series of missions, with the earlier mission(s) providing technology stepping stones toward an NHST on the 2015–2020 time scale, might provide one approach. Specifically they could include the enhanced Explorer–class telescope, an ∼4–8 m class UV–optical telescope with wide–field imaging and multi-object spectroscopy, and/or an ∼8 m class optical coronagraphic telescope (for earth–like planet detection and limited photometric/spectroscopic characterization of detected planets) with capability for wider field imaging and spectroscopy.

The technologies that will play a major role in these optical–UV missions include optical systems, possibly with elliptical optics, deformable mirrors, and almost certainly light–weight optics, with particular attention paid to optical throughput from coatings. The overall efficiency of these missions will be enhanced by high-QE detectors, high efficiency spectrograph gratings, multi-object spectrographic capability, and new polishing technology, especially for coronagraphs. New concepts for coronagraphs are currently attracting great interest. Any coronagraphic telescope will require careful systems design, with particular attention to stability and thermal control. Extensive modeling and ground demonstrations will be needed in these areas.

Detectors continue to be a challenge, with the highest priority given to improved UV performance, particularly for the near-UV. We need QE much greater than the current 10% in the near-UV, and the far-UV QE should improve from the current 30-40% to 70-80%. A long-term goal should be to attain wavelength-multiplex efficiencies through energy-resolving detectors. Currently, UV detectors have only a fraction of the DQE of optical CCD detectors. Performance (read noise, QE, CTE, etc) of current CCD detectors in the optical (300 nm to 1100 nm) approaches that required, but a serious concern for such detectors remains the degradation that they undergo in a high radiation environment, since the likely location for all new major facilities is well beyond low earth orbit. The development of new types of devices may be needed if we are to have optical detectors of comparable performance to CCDs that also have adequate lifetime in a high radiation environment,

A key area for consideration of the implementation of new missions is the role that human space flight might play. This decision is particularly important in the aftermath of the Columbia Shuttle tragedy. The role of humans in a future NHST mission could be much larger than is planned for more near–term missions (e.g., JWST). The trade studies have yet to be made, but the human space program could be involved through post–launch deployment and testing, and possibly subsequent servicing, although that would more likely be robotic given the likely orbits.

The potential of adaptive optics systems on large ground-based telescopes requires further evaluation. While their utility in the near–infrared at wavelengths beyond $\sim 1\ \mu$m is clearer, the optical regime presents huge challenges for AO on large ground–based telescopes. This was emphasized at the Chicago meeting by one speaker, Jerry Nelson, who summarized the performance goals for the California Extremely Large Telescope (CELT) using multi-conjugate AO in the 2012 timeframe. The Strehl ratios quoted were small compared to those routinely enjoyed now by HST users. It is likely that, even well into the next decade, AO will not be competitive with optical space telescopes, and certainly not over significant fields of view.

The timescale to plan for Observatories like HST, Chandra, SIRTF and JWST is quite long, measured more in decades than years. This duration results from the extraordinary technical challenges faced when we take such giant steps in capability, and from the huge investments required for such missions. Yet, as HST and Chandra have shown, and as we expect from SIRTF and JWST, these major missions deliver remarkable scientific results. They not only deliver, but they do so in a cost-effective way. As difficult as this is to establish, the anecdotal sense that the path of astrophysics has been seismically shifted by HST and Chandra is born out by metrics ranking the discoveries from scientific missions. HST clearly stands out as #1 in such surveys, even in scientific discoveries per dollar The extraordinary returns from HST highlight why there is such strong support amongst the astronomical community for such capabilities in the future. The scientific issues addressed by HST remain some of the most exciting of our time, and the enthusiasm of the participants, young and old, at the Boulder and Chicago workshops reflected the scientific potential of its UV–Optical successor, NHST.

1 Introduction

This document summarizes the results of a major effort undertaken in 2002, aimed at exploring the scientific challenges in space Optical-UV astronomy in the 2010–2020 time frame, and considering the types of missions and technologies needed to reach these scientific goals.

The culmination of this activity was an international workshop: *Hubble's Science Legacy: Future Optical-Ultraviolet Astronomy from Space*, held at the University of Chicago on April 2-5, 2002, and co-sponsored by AURA, NASA, and ESA. About 130 people attended the meeting, presenting 52 oral and 22 poster papers on a wide range of scientific and technical topics. The participants also engaged in an active discussion during the many periods set aside for dialogue with the attendees. This report is a distillation of the principal ideas and conclusions that emerged from that meeting.

Several supplemental documents provide more detailed information on the HSL workshop and its related activities. The meeting program and participants can be found at:

http://www.aura-astronomy.org/hsl/
http://www.stsci.edu/stsci/meetings/HSL/HSLprogram.html.

In addition, full proceedings of the conference are being published in ASP Conference Series Vol. 291 (Sembach et al. 2003, in press). The meeting programis also given in the Appendix. At the conference many names were used for a potential successor to Hubble, e.g., HST^{++}, HST-II, SUVO, NHST. For clarity, combined with the clear scientific link to HST, we decided to use NHST throughout this document.

2 Background

A driving force behind the recent discussions regarding a successor to HST is the recognition that the gestation period for space astronomical observatories is very long. For example, the Space Infrared Telescope Facility, SIRTF, has been under development in various forms since the late 1970s. The concept was outlined in the 1980 Decadal survey (the "Field Committee Report" *Astronomy and Astrophysics for the 1980's, Volume 1: Report of the Astronomy Survey Committee* 1982). SIRTF was ranked as the highest priority program in the 1990 Astronomy Decadal survey (the "Bahcall Committee Report" *The Decade of Discovery in Astronomy and Astrophysics* 1991). SIRTF is currently scheduled for launch in April 2003 on a Delta II rocket.

Another example is NGST, the Next Generation Space Telescope, which was renamed the James Webb Space Telescope (JWST) and was the subject of extensive workshops and studies in the late 1980s and early 1990s (see *The Next Generation Space Telescope* conference in 1989 and the *Technologies for Large Filled Aperture Telescopes in Space* conference in 1992). NGST/JWST received a major boost from a study in 1995, the *HST & Beyond* committee report, and it has now passed a major milestone with the selection of a prime contractor headed by TRW (Northrup-Grumman) and Ball Aerospace & Technology Corporation. The earliest that JWST will be launched is June 2010, although some space astronomers forecast an even later launch date.

The Hubble Space Telescope has been the most productive scientific space mission of all time. Its unique high resolution imaging and UV capabilities will disappear around 2008–2010 as it ages following its last servicing mission in 2004/2005. As the above examples suggest, we are already late in taking the ground-breaking steps on a successor to HST that could be launched during the first half of the next decade.

The success of HST would suggest that a successor is an obvious choice. However, the very large investment in time, effort and funding needed to bring about a mission of the scale of HST, SIRTF or JWST requires us to make a compelling scientific case for the next large UV-Optical mission. This scientific case will be evaluated with a critical eye by skeptical scientific committees, NASA senior scientists and managers, budget agencies and congressional committees.

Two questions play a central role in discussions of an HST successor:

- What are the major science issues of the next decade?
- What role would a Optical–UV space telescope play in the resolution of those questions?

After considerable discussion with senior scientists at NASA and the Space Telescope Science Institute, the Space Telescope Institute Council (STIC) recommended to AURA that they sponsor a workshop as the next step in addressing these questions. This workshop was designed to build on the earlier workshop devoted to studying a successor to HST, the 1998 conference on *Ultraviolet-Optical Space Astronomy Beyond HST* held in Boulder, Colorado. The Boulder conference led to a NASA-sponsored study and a scientific report entitled *The Emergence of the Modern Universe: Tracing the Cosmic Web.* The Ultraviolet-Optical Working Group or UVOWG subsequently recommended either a 4m or 8m successor to HST known as the Space Ultraviolet-Visible Observatory (SUVO). Details of the UVOWG study (Shull et al. 1999, astro-ph/9907101) can also be found at:
http://origins.Colorado.EDU/uvconf/UVOWG.html.

The second workshop, *Hubble's Science Legacy: Future Optical-UV Astronomy from Space*, ultimately came to be co-sponsored by AURA, NASA and ESA and was generously hosted by the University of Chicago. It was held in the Ida Noyes Hall at the University of Chicago from April 2–5, 2002. The workshop's goal was to look beyond HST at the scientific challenges of the next decade, and then at the types of missions and the technologies needed to reach those goals.

Invited speakers included experts in a broad range of science areas, along with experts on the requisite technologies and those with experience in missions and projects with overlapping scientific objectives. A special effort was made to include a diverse representation among the speakers, ranging from senior scientists with a broad experience and perspective to young scientists who will be the primary users of these future facilities. The breadth of their contributions can be seen from the titles of the talks and poster papers in the program (see the Appendix to this document, which also includes the workshop announcement and the scientific organizing committee).

An outcome of the workshop was a request by NASA HQ for a "White Paper" that summarized the main results of the workshop, and this document is the product of that effort. An earlier summary draft of this document was circulated as input to the 2003 OSS Roadmap studies. The goal of this document is to highlight the scientific promise and technical challenges that were identified for NHST at the workshop. It is intended as a starting point for more in-depth science planning and technological studies that are already underway.

3 Key Science Problems in 2010–2020

The science discussions focussed on two objectives, identifying key science problems (so-called killer applications or "killer-aps") which individually or collectively would form defining objectives for a future space facility. Other major science programs should play a role as science drivers for such facilities. Several such core applications were identified (listed below in ascending order of distance):

3.1 Critical Science Applications (NHST Killer-Aps)

3.1.1 Planet Detection and Characterization

A diffraction-limited visible-UV space telescope in the 8m class with high-rejection coronagraphic capabilities would be capable of directly imaging nearby analogs to our own solar system, including Earth-like planets around nearby stars. When coupled to a high-resolution UV-visible spectroscopic capability it would be possible to detect the spectroscopic signatures of terrestrial atmospheres and (possibly) biomarkers. Quite independently, synoptic spectroscopic monitoring of nearby stars would be capable of detecting planets and their atmospheres via occultations (e.g., Charbonneau et al. 2001). Such a facility would be a powerful complement to other interferometric planet-finder facilities. Our group was not the first to identify this area as a key science driver for a large diffraction-limited space telescope. Such an approach has been under active study by the TPF project for some time.

3.1.2 Protoplanetary Disks and Star Formation

The increases in spatial resolution, sensitivity, and coronagraphic imaging enabled by a 4–8m class HST successor facility would open up the possibility of directly imaging the protoplanetary disks around newly formed stars in nearby star-forming regions. High-resolution multicolor maps of such disks will greatly enhance our understanding of their dynamics and properties of the dust. They can also allow indirect evidence for the existence of planets. These capabilities have a strong synergy with planned observations with JWST and ALMA in the infrared to submillimeter.

3.1.3 The Cosmic Baryon Cycle

Observations over the past several years with HST, the Far-Ultraviolet Spectroscopic Explorer (FUSE), and groundbased 8-10m class groundbased telescopes have begun to reveal the complex physical interplay between evolving galaxies, their extended gaseous halos, and the intergalactic medium that contains most of the baryonic mass of the universe. These ultraviolet spectrographs have shown that 30–50% of the missing baryons probably reside in the multiphase IGM, detectable in the H I Lyα forest (warm diffuse gas) and in the O VI absorbers (hot shocked phase). However, we still do not understand the sizes and topologies of this "cosmic web" of baryons, nor do we know the sites of metallicity production and the extent of metal transport from early galaxies into the IGM. Ultraviolet and visible wavelength spectroscopy on a high-throughput 4–8m class space telescope would provide sensitivity gains of 100 times or more over current HST capabilities, and allow tens of thousands of cosmic sightlines to be probed (as compared to tens of sightlines today). This would allow us to construct a complete, self-consistent picture of the recycling of matter, radiation, and mechanical energy between galaxies and the IGM, over cosmic epochs ranging from the initial assembly stages of galaxies to the current epoch. A detailed discussion of this application can be found in the SUVO study.

3.1.4 Formation of Hubble Sequence and Central Black Holes

A large-aperture diffraction-limited optical-UV telescope would allow us to trace the evolution of galaxy morphologies and the formation of galactic bulges and disks, with very substantial reductions in the surface-brightness biases that plague current measurements with HST. At the same time, deep imaging of the nearest galaxies would enable us to reconstruct the fossil record of star formation directly, using color-magnitude diagrams extending to the main sequence in the bulges and disks of galaxies, where the bulk of the luminous baryonic mass resides.

The extraordinary spatial resolution and sensitivity provided by such a telescope would also allow us to obtain direct measurements of the stellar and gaseous kinematics in the centers of hundreds of galaxies, and address the role of the massive central black holes in the formation and evolution of their parent galaxies.

3.1.5 Cosmology

Although enormous progress in this field has been made by the Wilkinson Microwave Anisitropy Probe (WMAP), further progress is anticipated from HST, Planck, LSST, and other planned facilities (e.g., from SNAP-like missions). A large-aperture Hubble successor telescope will make unique contributions toward characterizing the dark matter and dark energy in the universe. The calibration of the cosmic distance scale to ±1% with Cepheids, ultra-precision weak-lensing measurements, and precise measurements of high-redshift supernovae all have the promise of constraining the cosmic equation of state in ways that are complementary to those planned for these other facilities.

3.2 Other Core Science for NHST

The applications highlighted above offer the promise of critical breakthroughs in their respective subject areas, and could individually or collectively form the foundation of the scientific justification for a Hubble successor mission. The workshop also revealed a wealth of key science projects that by themselves may not be as compelling, but would add substantially to the scientific promise and capabilities of such a facility. Examples of these include:

- Monitoring planetary weather for planets in the outer solar system, and direct imaging of asteroids, Kuiper Belt objects, and comets
- Direct imaging and helioseismological mapping of nearby stars, and monitoring of the activity cycles of other stars
- Precision distances to any galaxy in the local supercluster, and the construction of a precise 3D map of the local galactic neighborhood

3.3 The Importance of Discovery Space

Several speakers, most notably Martin Harwit, emphasized that many of the most significant discoveries of a new facility are *not* anticipated in advance. An independent figure of scientific merit for a potential facility is the amount by which it opens previously unexplored discovery space. Order-of-magnitude advances in spatial resolution, sensitivity, wavelength coverage, or spectral resolution can yield spectacular scientific gains. HST is a testament to this. A large optical-UV successor to HST offers a comparable discovery space in several aspects. For example, an 8m diffraction-limited telescope with high-throughput optics would offer the following:

- A limiting magnitude for UV spectroscopy a factor of 20 times fainter than HST with the Cosmic Origins Spectrograph (COS)
- Imaging with a limiting magnitude more than ten times fainter than HST with the Advanced Camera for Surveys (ACS) or the Wide Field Camera 3 (WFC3)
- A diffraction-limited resolution of <10 milliarcseconds in the blue and ultraviolet, matching the expected performance of an adaptive optics camera on a 30m groundbased telescope at 2 microns
- A diffraction-limited field of view limited by detector coverage (up to several arcminutes), compared to fields of order arcseconds with high-order adaptive optics in the groundbased visible that also have lower Strehl and less stability.
- Photometric accuracy and stability that is unobtainable from the ground

3.4 The Impact of Adaptive Optics

The likely capabilities on the ground with large optical telescopes and the potential of adaptive optics (AO) in the near–infrared at wavelengths beyond $\sim$1 μm also need to be considered when discussing future Optical-IR telescopes. The discussion at the workshop made it very clear that the optical regime presents huge challenges for AO on large ground–based telescopes, even well into the next decade, and will not be competitive with optical space telescopes, at least over significant fields of view. A very useful assessment of this in the near-term can be found in the recent report by Glenn Schneider et al. (2002) on *Domains of Observability in the Near-Infrared with HST/NICMOS and Adaptive Optics Augmented Large Ground–Based Telescopes.*

4 Core Capabilities for NHST: Three Models

When considering both the key science applications and the discovery potential outlined above, a few key technical capabilities were cited repeatedly.

- High-throughput (wavelength-multiplexed) UV spectroscopy
- Wide-field optical diffraction-limited imaging
- High dynamic range optical coronagraphy

Interestingly, during the three days of science presentations spanning the full range of astronomical applications, the requisite technical requirements tended to center on at least one of the capabilities above. Three distinct types of facilities emerged from these discussions.

4.1 UV-Optimized Mid-Sized Telescope

For many of the scientific applications, most notably those centered on the cosmic baryon cycle, the interstellar medium within and between galaxies, and many applications in stellar and planetary astronomy, the most critical capability is high-throughput UV (and visible) spectroscopy. Order-of-magnitude gains could be made, even by a 3-4m class telescope equipped with high-efficiency optics and high quantum efficiency UV detectors. This option was explored at length in the SUVO study, which recommends a telescope with these capabilities. Such an instrument would not have to be diffraction limited at the shortest wavelengths, and this may bring it within the reach of an enhanced Explorer line (the "Einstein Probes) as was explored by the SEU Roadmapping Committee.

4.2 Wide-Field Large Diffraction-Limited Telescope

Many of the killer applications highlighted earlier rely on order-of-magnitude gains in sensitivity that can only be realized by diffraction-limited point source imaging and/or spectroscopy. An 8m class optical-UV telescope would enable nearly all of the applications (except for those requiring high-contrast coronagraphic capability– see below), and realize an enormous discovery space over HST. However there was considerable difference of opinion expressed over the technical (and financial) feasibility of such a large diffraction limited telescope, even 10–15 years from now. A 4m class diffraction-limited telescope could meet many of the goals, including all of the SUVO objectives. Such a mission could serve as a technological stepping-stone toward a larger, possibly coronagraphic TPF-class facility.

4.3 8m Class Optical (Coronagraphic) Telescope

Not surprisingly, the most ambitious (and scientifically most compelling) objectives of detecting and characterizing earth-like planets, as well as high-contrast imaging of protoplanetary disks and related phenomena, are the most technically challenging. They require at a minimum a 8–10m diffraction limited telescope with coronagraphic capability and active wavefront control. Such a facility is under active study as one of the two technical paths toward TPF.

An 8m-class telescope also is key to several of the other high-priority science goals outlined here and discussed at the workshop. For example, the small size of high redshift galaxies (at $z/sim2-4$) and the strong impact of the $(1+z)^4$ surface brightness dimming may make an 8m-class diffraction-limited telescope essential for quantifying the evolutionary processes in galaxies in a key formative epoch $/sim10$ Gyr ago. The technical studies for TPF might valuably be broadened to assess the issues associated with such a capability.

5 A Phased Approach to NHST?

As a fundamental boundary condition for this study, we deliberately refrained from advocating a particular mission architecture or even ranking the three approaches that are highlighted in the previous section. The goal of this exercise was to articulate the scientific case for a Hubble successor facility (or facilities) and identify the critical technologies needed to make such facilities a reality. It will remain for other groups and the normal peer evaluation process to advocate for and select specific mission concepts.

Nevertheless, it is important to emphasize that many of the critical technologies required for an imaging TPF (or its equivalent) will need to be demonstrated on a smaller scale. A series of two or more focussed and phased missions may be able to meet both the technical and scientific objectives highlighted in this report. An example of such a phased program could be a ∼4m telescope that is a TPF precursor (called "TPF-lite" at the workshop), leading eventually to a 8 m class telescope that has the capabilities to tackle the Optical-UV science questions of the next decade. However, many of the key science issues identified here are likely to remain high on the agenda of the astronomical community. This might well be an optical TPF with those additional capabilities (wider field primarily) needed for more general astrophysical goals.

However, one predicts demanding challenges of detecting earth-like planets and characterizing their atmospheres, in order to confirm or reject the existence of extensive life. These tasks may require a telescope that is so demanding technically that it becomes impractical to add the general-purpose science capabilities. A separate telescope for broadly–based Optical–UV science may be the only practical path. It is likely that many of the technological developments carried out for an optical-TPF will be directly transferable to a more general purpose observatory. Thus, a continuing close coupling between these programs will be mutually advantageous. **The use of a phased approach not only allows us to achieve our scientific objectives but allows us to do so in a way that maximizes the scientific return.**

6 Realizing NHST: Key Technologies

Making any of the facilities a reality presents technical challenges in several key areas, including optics, detectors, and systems design. However for facilities which might be launched in the 2015 timeframe, a relatively modest investment in key areas now can reap major dividends later. In the near-term these would come about from developing synergistic relationships with other missions that are at more advanced stages of development. The experienced engineering groups working those missions could potentially be used to identify technologies suitable for NHST and to highlight those areas that present the likely greatest challenges for the new mission.

In brief summary, the following areas need more technology funding to bring the UV/Optical technology to an adequate state of readiness for the next missions:

- **Optical Systems**: elliptical optics; deformable mirrors, light-weight optics; coronagraphic approaches
- **High-Throughput Optics**: coatings, gratings, polishing technology
- **Systems Design**: stability, thermal control, wavelength-multiplexing spectrographs
- **Detectors**: high-QE UV detectors, radiation-hardened optical detectors
- **Manned/Robotic Deployment and Testing**: post-launch and possibly subsequent servicing

As discussed in great depth in the UVOWG White Paper, the NHST Mission Concept will require significant NASA technology investments. Throughput is the single most important technology driver for the future of UV-optical space astronomy, both for spectroscopy and for wide-field imaging. The key areas are: detectors, large light-weight precision mirrors, optical materials and coatings, and precise optical elements (gratings and micro-mirrors). The following short list highlights the most critical needs identified by the UVOWG:

- Develop more sensitive UV detectors, with low background noise, high quantum efficiency, large dynamic range, and large formats.
- Space-qualify large mosaics of low-noise, high-QE CCD detectors (at least $16K \times 16K$) for wide-field imaging cameras in the optical and near-UV.
- Develop micro-mirror arrays for use in multi-object and integral-field spectrographs in the UV and visible.
- Develop large, lightweight precision mirrors for use in the UV/optical Although SUVO could be done with a 4m monolith, the extension to an 8m aperture will likely require segmented deployable optics.
- On a very long time scale, develop "3D" energy-resolving detectors such as photon-counting superconducting tunnel junction (STJ) or transition-edge sensor (TES) devices. These cryogenic detectors have the potential to revolutionize UV-optical astrophysics. This cryogenic technology would be shared with other missions (e.g., far-IR and sub-mm).

7 Concluding Remarks

As we have noted, the timescale for observatories like HST, Chandra, SIRTF and JWST are long, measured more in decades than years. This results from the extraordinary technical challenges that face us when we take such giant steps in capability, and from the huge investment that such missions require. Yet, as HST and Chandra have shown, and as we expect from SIRTF and JWST, these major missions truly deliver scientifically and in a cost-effective way. We have the anecdotal sense that the path of astrophysics has been seismically shifted by HST and Chandra, born out by metrics ranking Hubble's scientific discoveries "numero uno". The extraordinary returns from HST highlight why there is such strong support amongst the community for such capabilities in the future. The scientific issues addressed by HST remain some of the most exciting of our time, and the enthusiasm of the participants, young and old, at the Boulder and Chicago workshops reflected the scientific potential of its successor, NHST.

8 ACKNOWLEDGEMENTS

The authors appreciate the efforts and thoughtful input of our astronomical colleagues, which built on the 2002 Chicago workshop. We thank the participants of that workshop for their contributions, excellent talks, and extensive discussion. The conference was successful because of the generous support from NASA thatallowed many young scientists to attend. The support of ESA and ESO enabled us to bring many international visitors. The organizing committees (scientific and local) also gave generously of their time and played a major role in the success of the workshop, as did the editors of the proceedings on which future workshops will build.

9 APPENDIX

9.1 Workshop Announcement

In 2010 the Hubble Space Telescope is expected to have completed its two–decade mission. Its enormous scientific legacy will be furthered in part by other missions, including the Next Generation Space Telescope, but the lack of optical–UV capability in space after 2010 will likely have a significant scientific impact. Progress on many key astrophysical problems will need Hubble–like capability – namely diffraction–limited imaging at optical and near–ultraviolet wavelengths and high–throughput UV–spectroscopy.

Recognizing the impact of the science produced by HST, and the scientific potential of a larger–aperture successor, AURA, NASA, and ESA are co–sponsoring a workshop to consider the opportunities presented by optical and UV astronomy in space in the next decade. We invite the international astronomy community to consider scientific goals and accomplishments achievable with a large new optical–UV telescope in space, with potentially multiples of Hubble's resolving power and even greater multiples of its collecting area. We encourage new initiatives and challenging questions in scientific areas not capable of being addressed by HST that will be amenable to discovery and study by such a powerful optical-UV telescope.

The most important objective of the workshop is to identify the compelling science questions that remain unanswered, and the corresponding scientific breakthroughs that could be achieved with optical–UV space telescopes. It will also address the likely performance requirements needed to achieve these scientific goals, and identify the technical challenges and hurdles that need to be overcome in the next decade if optical–UV successors to HST are to become a reality in the 2010–2020 time frame.

The scope of the scientific discussion will be very broad, encompassing problems in cosmology, extragalactic astronomy, stellar populations, the ISM/IGM, star and planet formation, stellar astrophysics, and solar system astronomy, all considered in the context of other ground and space missions producing discoveries in the 2010–2020 time frame. Optical–UV capability was recognized as likely to play a key role for progress in most of these areas. The workshop is not intended to discuss or promote specific telescope or mission concepts, but instead to focus on the scientific promise and rationale for a large Optical-UV space telescope, and the range of technical capabilities that might be needed to meet these scientific objectives.

Scientific Organizing Committee

G. Illingworth (UCSC, Co–chair)
S. Beckwith (STScI)
C. Cesarsky (ESO)
J. Crocker (BATC/JHU)
A. Dressler (Carnegie Obs)
A. Dupree (CfA)
S. Faber (UC Santa Cruz)
W. Freedman (Carnegie Obs)
A. Giménez (ESA)
H. Hasan (NASA HQ)
R. Kron (Chicago)
S. Lilly (NRC)
R. Kennicutt (Arizona, Co–chair)
J. Lunine (LPL)
F. Macchetto (ESA/STScI)
J. Mould (NOAO)
W. Oegerle (NASA/GSFC)
E. Schreier (STScI & AUI)
J.M. Shull (Colorado)
L. Simmons (JPL)
E. Smith (NASA HQ)
D. Spergel (Princeton)
C.M. Urry (Yale)

9.2 Workshop Program

Tuesday, 2 April 2002

Introduction

Welcome, Opening Remarks & Workshop Goals
Bill Smith (AURA), Garth Illingworth (UCSC), Chris Blades (STScI)

1. Context: Key Problems in Astrophysics in 2010-2020

Session Chairs: Bill Smith (AURA), Bruce Margon (STScI)

The Optical-IR Astronomy Landscape in 2015
Alan Dressler (Carnegie Observatory)

Thoughts on a Powerful New Ultraviolet Facility
Martin Harwit (Cornell University)

Highlights of the SUVO Study
J. Michael Shull (University of Colorado at Boulder)

Building the Vision of the Future in Space Astronomy & Physics
Phil Crane (NASA Headquarters)

The Future of Optical Astronomy in ESA's Science Programme
Alvaro Gimenez (ESTEC, The Netherlands)

Ground-based Astronomy in 2010-2020
Roberto Gilmozzi (ESO, Germany)

2. Stellar Astrophysics and Evolution

Session Chair: Sally Heap (GSFC)

The Future of Supernova Research
Peter Garnavich (University of Notre Dame)

Accretion Binaries and Other Stellar Problems
John Hutchings (Dominion Astrophysical Observatory)

Cool Stars And The Future
Andrea Dupree (Harvard-Smithsonian Center for Astrophysics)

Evolutionary and Pulsational Properties of Intermediate-Mass Stars: Current Odds and Future Perspectives
Giuseppe Bono (Observatory of Rome, Italy)

3. Star and Planet Formation

Session Chair: Richard Kron (University of Chicago)

Problems in Star and Planet Formation
Lee Hartmann (Harvard-Smithsonian Center for Astrophysics)

Beyond the Cosmic Veil: Space-based Star and Planet Formation Research after SIR TF & JWST
Michael Meyer (Steward Observatory, University of Arizona)

High Contrast Imaging and the Disk/Planet Connection
Glen Schneider (Steward Observatory, University of Arizona)

Wednesday, 3 April 2002

4. The Solar System
Session Chair: Paul Feldman (Johns Hopkins University)

Solar System UV/Optical Astronomy & the Future of Space-based Observations
Walter Harris (University of Wisconsin)

HST Observations of Planetary Atmospheres
John Clarke (Boston University)

Solar System: Satellites and Summary
Melissa McGrath (Space Telescope Science Institute)

5. Extra-solar Planets
Session Chair: John Trauger (Jet Propulsion Laboratory, Caltech)

NASA's Origins Theme: Results from TPF Architecture Studies
Chas Beichman (Jet Propulsion Laboratory, Caltech)

Strategies for Extra-Solar Planet Characterization with Large Aperture Telescopes
Mark Clampin (Space Telescope Science Institute)

Extra-solar Planets and Biomarkers
Wes Traub, Harvard-Smithsonian Center for Astrophysics)

The Occurrence and Observability of Giant Planets and Terrestrial Planets Around Other Stars [PDF (3MB)]
Jonathan Lunine (Lunar and Planetary Laboratory, University of Arizona)

6. Nearby Galaxies and Stellar Populations
Session Chair: Carol Christian (Space Telescope Science Institute)

Stellar Populations Science in the Era Beyond Hubble and JWST
R. Michael Rich (UCLA)

Evolutionary Processes in Galaxies
Eva Grebel (MPIA, Heidelberg, Germany)

Stellar Population Challenges for the Next Decade
Harry Ferguson (Space Telescope Science Institute)

7. The Interstellar Medium & Intergalactic Medium
Session Chair: Blair Savage (Wisconsin)

Studies of the IGM with the Next Generation Space Facility
Jill Bechtold (Steward Observatory, University of Arizona)

Probing Chemical Evolution, Dust Formation, Nucleosynthesis, and Star Formation in the ISM of $z < 1$ Galaxies
Jason Prochaska (Carnegie Observatories)

Studying the Gaseous Phases of Galaxies with Background QSOs

Jane Charlton (Penn State University)

Probing Baryons in Galactic Halos and Gas Near Galaxies

Ken Sembach (Space Telescope Science Institute)

Precise measurements of Hydrogen, Deuterium, and Metals and the structure and physics of the Nearby Interstellar Medium

Jeff Linsky (University of Colorado at Boulder)

Thursday, 4 April 2002

8. Black Holes, AGNs & Galactic Centers

Session Chair: Duccio Macchetto (Space Telescope Science Institute)

The Formation and Evolution of Super-Massive Black Holes

Laura Ferrarese (Rutgers, The State University of New Jersey)

Integral-Field Spectroscopy of Galactic Nuclei

Tim de Zeeuw (Sterrewacht Leiden, The Netherlands)

The Structure and Energetics of Active Galactic Nuclei

Brad Peterson (Ohio State University)

9. Distant Galaxies & Physical Evolution of Galaxies

Session Chair: Don York (University of Chicago)

Galaxy Formation Now and Then

Matthias Steinmetz (Astrophysikalisches Institut Potsdam, Germany)

Measuring the Influence of Supernovae at High Redshift

Kurt Adelberger (Harvard-Smithsonian Center for Astrophysics)

A Theorist's Wish List: What We Want to Know About Galaxy Formation and How Hubble's Successor Can Help

Rachel Somerville (University of Michigan)

Galaxies in Groups and Clusters: Linking Mpc to pc Scales

Erica Ellingson (University of Colorado at Boulder)

10. Cosmology, Dark Matter & Dark Energy

Session Chair: William Oergerle (NASA Goddard Space Flight Center)

Gravitational Lenses

Chris Kochanek (Harvard-Smithsonian Center for Astrophysics)

Dark Matter and Dark Energy: The Critical Questions

Mike Turner (University of Chicago)

11. Technology I.

Session Chair: Jim Green (University of Colorado)

Long-Range Technology Planning in NASA's Office of Space Science

Harley Thronson (NASA Headquarters)

Technology Considerations: The First Steps
Larry Simmons (Jet Propulsion Laboratory)

UV and Optical Detectors for Space - Progress and Prospects
Bruce Woodgate (NASA Goddard Space Flight Center)

Superconducting Tunneling Junctions for Optical-UV Astronomy
Tone Peacock (ESTEC, The Netherlands)

Coronagraphs for Terrestial Planet Finding
David Spergel (Princeton University)

The Darwin-GENIE Experiment: An ESA-ESO Partnership
Ph. Gondoin (ESTEC, The Netherlands)

Friday, 5 April 2002

12. Technology II.

Session Chair: David Leckrone, NASA Goddard Space Flight Center)

The Potential of Ground Based Telescopes
Jerry Nelson (Lick Observatory)

Ground vs. Space Platforms for Future Large Optical/Infrared Telescopes
Roger Angel (Steward Observatory, University of Arizona)

Human Construction and Servicing of Space Observatories Beyond Low Earth Orbit
Joe Rothenberg (formerly NASA Headquarters)

Large-Optics Technology Lessons from Ball's JWST and TPF Programs
Steve Kilston (Ball Aerospace & Technologies Corp)

Starting a New Project: Thoughts from JWST
John Mather (NASA Goddard Space Flight Center)

13. Summary & Concluding Remarks

Session Chairs: Robert Kennicutt (Arizona), Garth Illingworth (UCSC)

HST++ Summary
Jeremy Mould (National Optical Astronomical Observatories)

The Local Universe: The Emergence of Life
Steve Beckwith (Space Telescope Science Institute)

Hubble's Science Legacy: A Technical Summary
Jim Crocker (Lockheed Martin Space Systems Company)

Hubble Science Legacy Workshop: Closing Remarks
Hashima Hasan (NASA Headquarters)

9.3 Poster Papers

Some Comments on the Need for Ultra-High Resolution Spectroscopy of the Cool ISM with a Future UV/Optical Space Telescope, *B.-G. Andersson*

High Resolution Observations of Supernova Remnants, *W.P. Blair*

Multiple Weak Lensing Deflections in the HDF-North, *T.G. Brainerd*

100 Times Faster and 3 Times Sharper: Background-Dominated Observations of Stellar Populations with an 8-meter Optical-UV Space Telescope, *T.M. Brown*

The Stellar Imager (SI): An Ultra-High Angular Resolution Ultraviolet/ Optical Observatory, *K.G. Carpenter, R.G. Lyon, C.J. Schrijver, L. Mundy, R.J. Allen, J. Rajagopal*

High Resolution Ultraviolet Quasar Absorption Line Spectroscopy of a $z \sim 1$ Galaxy Group, *J. Ding*

Constraining the Heliosphere: The Need for High-Resolution Observations of Nearby Interstellar Matter, *P.C. Frisch*

The Exquisite Spectrum of RX J1230.8+0115, *R. Ganguly, J. Masiero, J.C . Charlton, K.R. Sembach*

The HST Legacy and Future for High Spatial Resolution Spectroscopy of Winds and Outflows from Young Stars, *C.A. Grady, B. Woodgate, R. Kimble, S. Heap, T. Gull*

The HST Legacy and Future for High Contrast Imaging of Disks and Outflows from Young Stars, *C.A. Grady, B. Woodgate, C. Bowers, G. Schneider*

High Angular Resolution Combined with Excellent Spectral Performance: A Necessity for the Next Ultraviolet/Visible Space Telescope, *T.R. Gull*

A Detailed View of the Photosphere of the Hot White Dwarf G191−B2B from STIS, *J.B. Holberg, M.A. Barstow, I. Hubeny, M.S. Sahu, F.C.Bruhweiler, W.B. Landsman*

Resolving Star Forming Regions in Distant Galaxies: A Case Study with Blue Spheroid Candidates out to $z = 1$, *M. Im*

Sensing Absorption Lines from the Interstellar and Intergalactic Media at High Signal-to-Noise and Resolution: How Far Can We Go? *E.B. Jenkins*

Spatial Heterodyne Spectroscopy: An Emerging Technology for Interference Spectroscopy, *F.L. Roesler, J.M. Harlander, J.G. Cardon, C.R. Englert, R.J. Reynolds, K. Jaehnig, S. Watchorn, E.J. Mierkiewicz, J. Corliss*

Modeling the Breakup of Comet Shoemaker-Levy 9, K.J. Walsh, D.C. Richardson, *T.W. Rettig*

UV-IR Science Prospects with TES Imaging Arrays, *R.W. Romani, J. Burney , P. Brink, B. Cabrera, P. Castle, T. Kenny, E. Wang, B. Young, A.J. Miller, S.W. Nam*

Advances in MCP Sensors for UV/Visible Astronomy, *O.H.W. Siegmund, J.V. Vallerga, A.S. Tremsin*

The Physical Conditions and Metal Enrichment of Low-Redshift Interstellar and Intergalactic Media: The Benefits of High-Resolution Ultraviolet Spectra, *T.M. Tripp, D.V. Bowen*

Progress in the Fabrication of GaN Photcathodes, *M.P. Ulmer, B.W. Wessels, O.H.W. Siegmund*

The HST Legacy at Midlife: What Is Needed in the UV and Can It Be Done? *W. Wamsteker*

On the Ionization of Heavy Elements in Diffuse Interstellar Clouds, *D.E. Welty*