Hubble Boldly Goes: The Frontier Fields Program

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Summary

The Hubble Frontier Fields (HFF) program is a Director’s Discretionary Time (DDT) campaign to observe 4–6 strongly lensing galaxy clusters and, in parallel, adjacent “blank” fields with the aim of detecting and characterizing high-redshift galaxies. The program will capitalize on the lensing capabilities of the clusters to probe redshifts beyond $z \sim 10$, reaching galaxies with intrinsic luminosities thirty times fainter than those detected in the HUDF12. The associated blank fields will have sensitivity comparable to the parallel fields of the HUDF09, and will expand the areal coverage by a factor of three. Together, these measurements will enable Hubble to provide a preliminary peek at the distant universe accessible to the James Webb Space Telescope.

Introduction

Deep-field imaging designed to probe galaxy formation and evolution in the early universe is now well established as a key theme of the Hubble science program. Such was not always the case. Support for the original HDF DDT program was far from unanimous within the astronomical community. Some felt that the observations would offer little insight into galaxy formation, which many contemporary theoretical models predicted to be a sedate, gradualist process. Others worried that, so soon after the correction of Hubble’s vision at considerable tax-payer expense, there might be Congressional repercussions from investing ten days of Hubble time on a single project with a dubious prospect of returns. Those fears proved unfounded; the HDF revealed galaxy assembly to be an active, dynamic process—and provided iconic images that have now permeated the public consciousness. The original HDF, together with Keck 10-m spectroscopy of the brightest 125 galaxies in the field, validated the concept of photometric redshifts that have now succeeded in opening distant objects to analysis via multi-bandpass imaging.

The HDF lies at northern declination. Following its success, Hubble compiled matching observations of a field in the southern sky, the HDF-S. Since then, as each new servicing mission enhanced its scientific capabilities, Hubble has devoted considerable time and resources to deep-imaging programs that span a range of depth and areal coverage. Those programs include GOODS (the southern field within the CDF-S), the HUDF (within the CDF-S), COSMOS, HUDF09, CANDELS, UDF12, and 3D-HST. As with the HDF, each Hubble deep-imaging program has been supported by extensive complementary observations from other space observatories, notably Spitzer, Chandra and Herschel, together with substantial photometric and spectroscopic contributions from ground-based facilities. All told, over 3,000 orbits of Hubble observations (approximately one cycle) have been invested in major deep-field survey programs, with more than 800 orbits devoted to the 15-square-arcminute UDF alone. This wide panoply of multi-wavelength observation has revolutionized our view of the universe: $z \sim 1$ galaxies are demoted to “low-redshift” systems, the $z \sim 2–3$ peak in star formation now lies at “moderate redshifts,” and detection limits have been pushed through the era of reionization to the brink of cosmic dawn at $z \sim 10–12$.

The Hubble Deep Field Initiative

Given the substantial advances made in this field over the past 15 years—and the costs—can Hubble offer the prospect of further transformative science from another deep-field survey? Or should we sit back, focus on consolidating our gains, and wait for Webb to bring the next breakthrough? That, in essence, was the question that prompted the Hubble Deep Field Initiative (HDFI). Following discussions with the Space Telescope Users Committee and the community, the
Institute Director, Matt Mountain, chartered a science working group (SWG) chaired by James Bullock (UC Irvine) to examine how Hubble might extend our knowledge of the cosmic frontiers at high redshift. The SWG members were Mark Dickinson (NOAO), Steve Finkelstein (UT Austin), Adriano Fontana (INAF), Ann Hornschemeier-Cardiff (GSFC), Jennifer Lotz (STScI), Priya Natarajan (Yale), Alexandra Pope (UMass), Brant Robertson (UA), Brian Siana (UC Riverside), Jason Tumlinson (STScI), and Michael Woods-Vasey (Pittsburgh). As a secondary goal, the committee was asked to consider observations that would lay the groundwork for future Webb observations of the early universe.

Formally, the HDFI SWG was charged with the following tasks:

- Define the science case and a set of science goals for a new set of ultra-deep-imaging fields with sensitivity depths comparable to those of the HUDF and the HUDF09 infrared follow-up. Provide an assessment of the urgency of pursuing this science.
- Assess the prospects for near-field science that can be achieved with these deep-field observations.
- Recommend the locations and number of fields that should be obtained to meet the science goals defined for the HDFI.
- Recommend the suite of filters and exposure times necessary to accomplish the science goals defined for the HDFI.
- Solicit input from the astronomical community in defining the science goals and recommendations described in the above tasks.
- Produce a short (10–15 page) white paper describing the results of the above tasks by October 1, 2012.

The HDFI SWG was also constrained to identify a program that required no more than 800–1,000 orbits, which (like the HDF) could therefore be accommodated through DDT without impinging on GO allocations in Cycle 21 and succeeding cycles.

At the outset of the process, the community was asked to weigh in on the HDFI, and 32 white papers were received outlining a variety of techniques, programs, and constraints that the community felt should be taken into account. The SWG engaged in lively discussions through the summer and fall of 2012, thoroughly covering the pros and cons of a wide variety of programs, including duplicating the UDF at a different location, probing deeper within the UDF itself, adding deep grism observations in selected fields, obtaining blue/ultraviolet data in selected fields as a precursor for Webb, and using galaxy clusters as telescopes to probe the high-redshift universe. Those discussions resulted in a unanimous recommendation to the Director, and were summarized in the SWG’s report, submitted on November 21, 2012. The HDFI SWG report is available at http://www.stsci.edu/hst/campaigns/frontier-fields/.

After due deliberation, the director decided to go ahead with the program, renaming it “Hubble Frontier Fields.” The observations of four galaxy clusters will be executed in Cycles 21 and 22, and, dependent on the results of an interim review, with observations of the final two clusters in Cycle 23. The HFF decision was announced in the Cycle 21 Call for Proposals, issued on December 5, 2012.
The HFF program

The HDFI SWG recommended that the Institute director should pursue a joint strategy of deep imaging on six strongly lensing galaxy clusters, together with parallel observations of adjacent “blank” fields (Figure 1). Quoting from the report,

“[The HFF program] combines proven techniques for studying high-redshift galaxies in blank fields with the potentially revolutionary use of natural gravitational telescopes to exploit their magnification of the faintest galaxies in the distant universe. The blank fields will increase three-fold the area covered at comparable depth by the HUDF09 and its parallel fields, tracing the history of star formation and the growth of stellar mass with improved statistics and reduced cosmic variance. In the cluster fields, HST can reach high redshift galaxies as faint intrinsically as those that JWST can detect in blank fields, even down to the dwarf galaxies thought to be the progenitors of typical $L^*$ galaxies in the modern universe.”

The proposed observations reach magnitude limits comparable to the HUDF09 parallel fields, matching the second deepest images that we currently have for the high-redshift universe. The blank-field observations will therefore provide important constraints on cosmic variance at redshifts $z \sim 6–8$. Observations in the field have pushed to galaxies at redshifts $z \sim 8–10$. Nevertheless, it is important to recognize that those galaxies represent the tip of the luminosity function at those redshifts. The cluster fields imaged by the HFF program will not necessarily reveal more high-redshift galaxies, but they offer the potential to detect the intrinsically fainter galaxies that are the progenitors of galaxies like the Milky Way in the local universe. Moreover, intrinsically luminous galaxies might be amplified to the point where spectroscopic observations with Hubble or Webb become possible.

The HDFI WG made a number of recommendations regarding the development of the observing program. In particular, they identified the following criteria for selecting the target clusters:

- The clusters must be massive and among the strongest lenses known, with high magnification caustics for objects at $z \sim 4–10$ that fit within the WFC3-IR field of view. This requirement is most easily met by clusters at $z > 0.37$.
- The clusters must be observable with Hubble, Spitzer, and Webb.
- The cluster fields should have low zodiacal background and low Galactic extinction.
- To the extent possible, the blank fields should avoid bright stars and outlying structure due to the galaxy cluster.
- Every effort should be made to choose clusters that are observable by the Atacama Large Millimeter/submillimeter Array (ALMA) and the observatories on Mauna Kea.
- If possible, ancillary data should be available from Hubble, Spitzer-MIPS, Herschel, Chandra, and ground-based telescopes.

The HDFI WG recognized that satisfying every criterion for every cluster may not be possible. They noted that analyzing the cluster data depends critically on understanding the cluster magnification maps, and how those translate to the volume probed at high redshift. This is a specialized area of research, and they urged the Institute to provide the appropriate reference data and analysis tools to level the playing field for all potential participants in this community program.

Implementing the HFF program

The responsibility for executing the HFF program rests with a core implementation team of Institute staff led by one of the authors (JL). That team is receiving advice and guidance from a number of external science advisors. From the outset, Spitzer researchers have been closely involved in the HDFI. The Spitzer Director, Tom Soifer, has committed up to 1,000 hours for observations by the InfraRed Array Camera of the target fields, and Spitzer staff members are working closely with the Hubble team.
to coordinate and implement the observations. In addition, several key members of the community are serving as external science advisors to the program, providing advice throughout.

The Institute has taken steps to involve the community in every aspect of the HFF implementation process. Immediately following the program’s announcement and the release of the HDFI WG report, the community was solicited for additional input on the observing strategy, filter selection, and cluster selection. In addition, members of the community with appropriate expertise were contacted individually and invited to comment on various aspects of the program. Finally, a website (www.stsci.edu/hst/campaigns/frontier-fields/) and blog (https://blogs.stsci.edu/hstdfi/) are being maintained to keep the community informed of developments as they happen.

The HDFI WG report outlines a potential observing scheme coupling 70 orbits of red/far-red optical observations using the Advanced Camera for Surveys (ACS) with 70 orbits of imaging with the WFC3-IR camera. This scenario achieves magnitude limits matching those in the HUDF09 parallel fields. Following discussion with the community, those recommendations were modified slightly—adding F140W observations in the blank field—to give the filter selection illustrated in Figure 2. The resulting sensitivities are summarized in Table 1, where the AB magnitude limits represent 5σ detections of a point source, as measured in an aperture 0.4 arcsecond in diameter and corrected to total magnitude. The observations will be taken at two epochs approximately six months apart, with the telescope rotated by 180° between epochs to switch cameras between cluster and blank field. Orientation constraints typically limit the scheduling window at each epoch to 30–50 days. Further details on the observations, including the dithering strategy that will be adopted, can be found at the Frontier Fields website.

### Table 1. The observing scheme for the HFF program

<table>
<thead>
<tr>
<th>ACS</th>
<th>orbits</th>
<th>AB$_{mag}$</th>
<th>WFC3-IR</th>
<th>orbits</th>
<th>AB$_{mag}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F435W</td>
<td>18</td>
<td>28.8</td>
<td>F105W</td>
<td>24</td>
<td>28.9</td>
</tr>
<tr>
<td>F606W</td>
<td>10</td>
<td>28.8</td>
<td>F125W</td>
<td>12</td>
<td>28.6</td>
</tr>
<tr>
<td>F814W</td>
<td>42</td>
<td>29.1</td>
<td>F140W</td>
<td>10</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F160W</td>
<td>24</td>
<td>28.7</td>
</tr>
</tbody>
</table>

The HDF WG provided an initial set of 16 candidate strong-lensing clusters. The implementation team supplemented that list with other candidates suggested by the community and matched their individual properties against the selection criteria defined by the Working Group. Particular attention had to be paid to the availability of suitable offset fields, since even moderately bright stars can cause significant problems in Spitzer IRAC imaging.

After considerable deliberations, the final selections are shown in Figure 3 and Table 2. All are strongly lensing, massive clusters, easily accessible with Hubble, Chandra, Spitzer, and Webb; all have previous Hubble and Chandra observations; four have been observed as part of the Hubble CLASH program. Four of the clusters are accessible by both ALMA and the telescopes on Mauna Kea; MACS0717.5+3745 is

### Table 2. The HFF clusters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Cycle</th>
<th>z</th>
<th>RA</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 2744</td>
<td>21</td>
<td>0.308</td>
<td>00:14:21.2</td>
<td>−30:23:50.1</td>
</tr>
<tr>
<td>MACSJ0416.1-2403</td>
<td>21</td>
<td>0.396</td>
<td>04:16:08.9</td>
<td>−24:08:28.7</td>
</tr>
<tr>
<td>MACSJ0717.5+3745</td>
<td>22</td>
<td>0.545</td>
<td>07:17:34.0</td>
<td>+37:44:49.0</td>
</tr>
<tr>
<td>MACSJ1149.5+2223</td>
<td>22</td>
<td>0.543</td>
<td>11:49:36.3</td>
<td>+22:23:58.1</td>
</tr>
<tr>
<td>RXCJ2248.7-4431</td>
<td>23*</td>
<td>0.348</td>
<td>22:48:44.4</td>
<td>−44:31:48.5</td>
</tr>
<tr>
<td>Abell 370</td>
<td>23*</td>
<td>0.375</td>
<td>02:39:52.9</td>
<td>−01:34:36.5</td>
</tr>
</tbody>
</table>

*Cycle 23 observations are contingent on the results from preceding cycles.*
too far north for ALMA, and RXJ2248.7-4431, one of the strongest Sunyaev-Zeldovich sources detected by the South Pole Telescope, is too far south for observations from Mauna Kea. All HFF clusters lie in locations that are at least moderately dark, some very dark.

The selected clusters already have sufficient Hubble observations in hand to allow the construction of magnification maps. Making such tools generally available is a priority and, to that end, Hubble issued a Request for Proposals in January of this year. Several responses were received, and contracts are being issued to a number of teams with the requirement that magnification maps for all six clusters are delivered prior to the start of Cycle 21 in October 2013.

All Hubble and Spitzer data taken for the HFF will have no proprietary time and will be available immediately to the community. The core implementation team will combine the Hubble observations to provide higher-level data products, which will be released within ~1 month of the final data acquisition at each epoch. In addition to the new Hubble and Spitzer observations, ancillary data from other observatories will be collected and made available to the community at a central website.

The Cycle 21 program

As announced in the Cycle 21 Call for Proposals, the community was encouraged to submit archival proposals to analyze HFF data, develop supporting theoretical tools, and/or submit observing proposals to obtain supplementary data. Submitted proposals will be reviewed in competition with all other Cycle 21 proposals by the Cycle-21 Time Allocation Committee. By policy, Institute staff members on the core implementation team may not serve as principal investigators on Cycle 21 proposals related to the HFF program, nor could they apply for funding as co-investigators on any such proposals.

The two clusters selected for observation in Cycle 21 are Abell 2744 and MACSJ0416.1-2403. Abell 2744, also known as Pandora’s Cluster, is a complex, massive system lying at redshift $z = 0.308$. The cluster has previous Hubble observations (PI R. Dupke: GO 11689) and has been identified as the product of a major merger involving up to four $10^{14} M_{\odot}$ separate clusters. Thirty to forty lensed images of background galaxies have already been identified in the system (Merten et al. 2011). To date, this cluster has only ACS observations, and the WFC3-IR imaging offers great potential for discovery. The HFF observations will focus on the southeast component, which is the most massive and well matched in angular size to the WFC3-IR field of view.

The second cluster scheduled for observation in Cycle 21, MACSJ0416.1-2403, lies at redshift $z = 0.396$ and has also been identified as a merging cluster (Mann & Ebeling 2012). Targeted by the CLASH Multi-Cycle Treasury program, multiply lensed images of more than 20 background galaxies are
The Evolution of the Hubble TAC Process

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Introduction

Hubble is now entering its 23rd year of operations and its 21st proposal cycle. Over the years, Hubble’s observing capabilities have developed and improved at each servicing mission with the addition of new instrumentation, and with growing expertise in utilizing the facility by the schedulers, the instrument-support scientists, and the community at large. At the same time, the detailed structure of the time allocation process has changed to enable the community to make more effective scientific use of the changing capabilities.

The evolution of the proposal process does not occur in a vacuum. The Institute consults regularly with the Space Telescope User Committee (STUC) and with scientists serving on each time allocation
committee (TAC). The Institute has also received advice from ad hoc committees, including the Second Decade Committee and the Space Telescope Institute Council (STIC) TAC Review Committee, and has been happy to profit from the experiences of other observatories.

Cycle 21 will see several additional changes to the Cycle 20 process, and the Call for Proposals outlines those changes. As with any step-by-step process, however, it can be difficult for the community to recall the underlying rationale for each modification. This article gives a brief historical overview, with the aim of describing how the process has changed and giving the context for those changes.

**Hubble proposal pressure**

The pressure from the community to use *Hubble* has been high throughout most of its history. Figure 1 shows the proposal oversubscription for each cycle; Figure 2 shows the pressure on observing time. The over-subscription level in Cycle 1 was 5:1 by proposals and 8:1 by orbits; the immediately following cycles showed a significant decline with the realization that *Hubble*’s primary mirror suffered from significant spherical aberration. The Cycle 4 deadline fell in September 1993, before the successful execution of Servicing Mission 1 (SM1) in December of that year, and the uptick of proposals in Cycle 5 clearly reflects the increased confidence of the community in *Hubble*’s refurbished capabilities. The oversubscription level has risen back to 5:1 in proposals and from 6:1 to 9:1 in orbits in the cycles following the most recent, highly successful, servicing mission, SM4.

![Figure 1: Hubble proposal pressure by number of proposals.](image)

![Figure 2: Observing pressure by orbits.](image)
The TAC Process

The Institute director allocates observing time on Hubble based on recommendations made by the TAC. TAC members are drawn from the astronomical community at large, and provide the broad range of expertise necessary to assess the wide variety of programs selected for consideration for Hubble observations.

Time on Hubble is allocated in cycles, with a typical duration of one year. Observing time is available through General Observer (GO) proposals (orbits) or snapshot (SNAP) proposals (targets), which are scheduled on an as-available basis in unused orbits between GO programs. Typically, 3500 orbits are available for GO science in a given cycle, and ~1000 SNAPs may be allocated, with ~300 executed. The community can also apply for support for archival research programs or Hubble-related theory programs.

TACs are constituted separately for each cycle, with typically 10–15% overlap in membership from one cycle to the next. Each TAC consists of a number of separate panels and a super-committee. Panels have 9–11 members commissioned to focus on a limited set of scientific topics. The super-committee comprises the panel chairs, the TAC chair, and 2–3 at-large members. Each panel (and the super-committee) reviews 50–80 proposals.

The scientific topic of each proposal is author-identified, using a set of standard keywords (e.g., Solar System, Cool Stars, Stellar Populations, AGN) and directed to a panel with the appropriate expertise. Conflicts of interest may arise for individual panelists, due, for example, to direct involvement in the proposal or a competing proposal, or close personal ties. Conflicted panelists do not vote on a proposal, and leave the room for the discussion in the case of major conflicts.

Figure 3: The success rate of proposals submitted by TAC panelists compared to results for non-panelists. In cases where a panelist’s proposal is reviewed by his/her panel, the success rate is a factor of two to three times higher than for non-panelists or for panelists whose proposal is reviewed by another panel. The creation of mirror panels for each scientific topic eliminates this bias.

In the first eight cycles, the TAC panels focused on a narrow range of scientific topics and considered all proposals within that range, regardless of size. Approximately 80% of the orbits were distributed among the panels, based on the proposal/orbit pressure. Each panel produced a ranked list of proposals, and the top-ranked proposals were allocated directly by the panels. The super-committee discussed proposals near each panel’s cut-off line, and allocated the remaining 20% of the orbits available to GO proposals. Figure 3 shows a consequence of the narrow topical focus of the individual panels. Panelists proposing for Hubble time would often find their PI-led proposals reviewed by the same panel the panelist/proposer was sitting on. While conflicted panelists left the room for the discussion, the results clearly show that they enjoyed a significant advantage over colleagues who were not members of that panel, and even colleagues at the same TAC meeting but on different panels. Starting in Cycle 9, the scientific scope of most panels was broadened to set up mirror panels, enabling panelist PI-led proposals to be directed to an alternative panel with the appropriate expertise. The exception was the Solar System panel, which remained a single panel through Cycle 16. Starting in Cycle 17, mirror panels were created by merging Solar System proposals with proposals for exoplanet and proto-planetary disk research.
Large and Treasury proposals

A further consequence of the initial TAC scheme was that very few Large proposals were selected; through Cycle 8, only 5 programs requesting more than 100 orbits were allocated time (990 orbits total, or 4.4% of the total allocation). This ran contrary to recommendations by the Space Telescope Advisory Committee (pre-launch) and the Hubble Second Decade Review Committee (2000) that Large proposals should receive ~30% of the total allocation.

To address this issue, from Cycle 9 onwards, approximately one-third of the time has been set aside for Large programs, which are reviewed and ranked by the super-committee. The boundary between Large and Regular programs was set at 100 orbits for Cycles 9 through 20; starting in Cycle 21, the boundary will be lowered to 75 orbits. The super-committee also reviews large-scale Archival Legacy programs and large SNAP requests (typically >200 targets).

Treasury programs were introduced in Cycle 11 and are similar in conception to Spitzer’s Cycle 1 Legacy programs. These are observing programs that address science areas of broad interest to the community. The data are generally non-proprietary. The programs are required to produce high-level data products, which are made available to the community and are supported at the appropriate level. As with Large programs, Treasury proposals are reviewed by the TAC super-committee.

Regular GO proposals

In the early Hubble cycles, GO proposals were categorized by size using a variety of criteria. As an example, in Cycle 3 the categories were Small (<10 hours), Medium (10–100 hours) and Large (>100 hours); in Cycle 4, the categories were Small (<60 hours) and Large (60 or more hours); in Cycle 5, the boundary between Small and Large proposals was set at 100 orbits, but was reset at 60 orbits in Cycle 6; and in Cycle 8, the categories were Small (<30 orbits), Medium (30 to 60 orbits) and Large (>60 orbits). With the introduction of the separate allocation for Large proposals in Cycle 9, Small and Medium proposals were combined into a single category, Regular proposals. Those proposals are reviewed by the panels, which allocate approximately two-thirds of the time available in each cycle. Each panel receives an orbit allocation based on the number of proposals directed to that panel and the number of orbits requested by those proposals. Typically, both factors receive equal weight, so a panel that received 8% of the GO proposals requesting 10% of the orbit total would be allocated 9% of the available orbits. Panels also provide comments on the Large proposals within their science area, and this advice is used by the panel chair as an aid to his/her discussion of those proposals on the super-committee.

Each panel works from a fixed orbit budget that seldom exceeds 200 orbits. As a result, Medium proposals (40–50 orbits or more) face a high threshold in winning time. From Cycle 10, a progressive subsidy was put in place to mitigate this issue: a pool of orbits was set aside at the outset; panel budgets were charged only for a fraction of the total orbit cost, with the remainder coming from the central pool. While initially successful, the increased proposal and orbit pressure since SM4 has limited the orbits available for the pool and reduced the subsidy to the extent that it is no longer effective (Figure 4). Consequently, starting in Cycle 21, Regular GO proposals will be divided into two

![Figure 4](https://via.placeholder.com/150)

**Figure 4**: The success rate of proposals as a function of size in the post-SM4 Hubble Cycles. In Cycle 20, only two proposals requesting more than 40 orbits were awarded time, and both were Treasury programs reviewed by the super-committee.
categories: Small proposals, for 1 to 34 orbits; and Medium proposals, for 35 to 74 orbits. Panels will review and rank both categories, but the panel orbit budget will only be charged for Small programs. Medium proposals ranked above the orbit cutoff line from each panel will be passed forward to the TAC super-committee for final review.

Joint proposals

Many science programs rely on combining observations spanning a wide range of wavelengths or angular scales. Hubble has entered into collaborative agreements with several other observatories in order to minimize the double jeopardy involved in submitting separate proposals for observing time. Starting in Hubble Cycle 9 (Chandra Cycle 2), Hubble and Chandra introduced the category of Joint HST-Chandra proposals; the Hubble TAC was given the authority to award up to 400 ksec of observing time on Chandra to Hubble proposals, while the Chandra TAC was able to award up to 130 orbits of Hubble time. This proposal category remains available in Cycle 21. Proposers are required to submit their proposals to the observatory whose observations constitute the major component of the science program.

Similar collaborative agreements are in place between Hubble and Spitzer and between Hubble and XMM. The XMM agreement was put in place in Cycle 20 and continues in Cycle 21. Joint Hubble-Spitzer proposals were introduced in Hubble Cycle 14 (Spitzer Cycle 2), and continued through Cycle 16 (5), corresponding to the completion of Spitzer’s cryogenic mission.

Cycle 16 included the category of Coordinated Hubble-Spitzer proposals, designed to provide an opportunity for larger-scale joint programs in Spitzer’s last cryogenic cycle. The standard program was reintroduced in Cycles 18 and 19, with the establishment of the Spitzer warm mission, and again in Cycle 21 with the authorization of the extended warm mission.

The Institute also has an agreement with the National Optical Astronomy Observatory (NOAO) that provides access to as much as 5% of the time available on most NOAO telescopes, corresponding to approximately 20 nights/year on most telescopes. No Gemini time is available. Since its inception in Cycle 10, a total of 58 nights have been awarded in support of Hubble proposals. NOAO TACs do not allocate Hubble time.

Multi-Cycle Treasury proposals

The typical Large and Treasury program recommended for approval by the TAC requests between 100 and 200 orbits, and only a handful of programs requesting more than 300 orbits have been successful in gaining time. It became clear in the cycles immediately preceding SM4 that an increasing number of projects require resources that extend beyond those available within a single cycle. Consequently, following extensive input from the community, discussion with the STUC, and the successful completion of SM4, a call was issued for large, high-impact science programs that would be scheduled over multiple cycles. Approximately 750 orbits from Cycles 18–20 were made available for such programs, with two-thirds of the time drawn from the Large GO allocation in each cycle and the remainder from Director’s Discretionary Time. (DDT). Three Multi-Cycle Treasury (MCT) programs were selected for execution: CANDELS, CLASH, and PHAT (see https://blogs.stsci.edu/newsletter/volume-28-issue-01/ for further details). Those programs will be completed in Cycle 20. Discussions are currently under way with the STUC on whether further opportunities for such programs should be considered for Cycle 22 or future cycles.

Director’s Time

The Institute director can specifically allocate up to 10% of the science orbits available in a given cycle as DDT. Generally allocated in response to proposals for time-sensitive observations of transient events—e.g., comets, planetary phenomena, supernovae, gamma-ray bursts—which could not have been predicted and cannot wait for the next formal Call for Proposals, DDT has also been used for larger-scale programs, such as the Shoemaker-Levy 9 program, Hubble Deep Field (HDF), the Hubble Ultradeep Field (UDF) and, most recently, the Frontier Fields Program. DDT also provided partial support of the three MCT programs.

Summary

The Hubble time allocation process has evolved over the years. In most cases, the changes introduced have been designed to address apparent inequities and/or to enable new opportunities for the community. We will continue to monitor and adapt the process in future cycles as science itself continues to evolve.

Acknowledgements: Thanks to Brett Blacker for providing the statistical data shown in Figures 1 and 2, and for providing Figures 3 and 4.
Hubble and Solar System Science

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Introduction

Observations of major and minor objects within the Solar System have formed a key part of Hubble’s program since its launch in 1990. Hubble’s unparalleled angular resolution, advanced spectroscopic and imaging instrumentation, and synoptical perspective are unique, invaluable assets for detailed investigations of planets and planetary phenomena. Everyone remembers the original “comet crash” into Jupiter by Comet Shoemaker-Levy 9 in 1994, which led to a series of iconic images and fully established the capabilities of the refurbished Hubble. Since then, Hubble has been a consistent contributor to Solar System research through such diverse programs as monitoring auroral activity and atmospheric phenomena on the gas-giant planets, tracking the interactions of moons in the Jovian and Saturnian systems, investigating the binary frequency and chemical composition of trans-Neptunian objects and Main Belt asteroids, and probing the atmospheric characteristics of Mars and Venus.

In recent years, however, questions have arisen in the community about Hubble support for Solar System science and how that support may have changed over the years, qualitatively or quantitatively. One question is whether panel review can capture the range of expertise required for the evaluation of the full diversity of Solar System proposals. Another is whether the Call for Proposals might create new types of opportunity for the Solar System community to use Hubble. Indeed, when in 1985 the Institute director asked the Space Telescope Advisory Committee (STAC) for advice on “key projects,” the STAC’s Solar System subcommittee recommended a special way of doing business—the “planetary campaign”—rather than a specific science project. Under this scheme, the community would define a campaign of observations on a planet or another type of planetary target, to be coordinated with observations from various facilities, including planetary missions. Culturally, the planetary campaign resembles the way planetary missions, consisting of multiple investigations, are formulated. Comet Shoemaker-Levy 9 provided a brilliant instance of a planetary campaign (See sidebar). Another example is the Cycle 15 Large Hubble program devoted to studying Jupiter and Saturn during the International Heliophysical Year, 2007. Indeed, Hubble is currently contributing to a coordinated multi-observatory campaign to observe Comet ISON.

References:


Figure 1: Hubble followed unexpected and dramatic changes in Jupiter’s atmosphere caused by collisions with comet fragments. The titanic blasts left Jupiter with a temporarily "bruised" appearance, caused by black debris that was tossed high above the giant planet’s cloudtops. Image credit: Hubble Space Telescope Comet Team and NASA.

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During the period from July 16–22, the world witnessed an extraordinary astronomical event: the collision between comet P/Shoemaker-Levy 9 and the planet Jupiter. The HST was a major player in the campaign to gather data on the impacts, devoting a total of 120 orbits to observations of the comet and Jupiter, including ~60 orbits during the impact week. Despite early apprehensions that the impacts might produce no detectable effects (no doubt the specter of comet Kohoutek was haunting everyone), the HST campaign proved to be a spectacular success. The high-resolution HST images provided unique details on the development of the plumes produced during the impacts and on the temporal evolution of the dramatic “scars” left on Jupiter. The HST spectroscopy of Jupiter’s atmosphere revealed the creation of exotic molecules (e.g., S2) at the impact sites. UV images showed strange aurorae at relatively low latitudes in the northern hemisphere, latitudes that were the magnetic conjugate points of the impact sites in the Southern Hemisphere. Observations of the comet itself placed constraints on the size and nature of the impactors (i.e., the comet vs. asteroid question). The HST observations of the impacts represent the first attempt to conduct a “Planetary Campaign,” a particular type of observing plan originally proposed by the Space Telescope Advisory Council in 1985 and modeled after observing objectives common to planetary flyby missions. Over 70 investigators participated in the campaign from a wide range of institutions. Media coverage of the event was unprecedented and provided a wonderful opportunity to get the public excited about astronomy.

Ferguson, H., Livio, M., Panagia, N., & Toolan, S. 1995, BAAS, 27, 587

The Institute constantly strives to improve its processes, and we take seriously questions raised by any members of our community. We plan to initiate a study of the issues identified by the Solar System community and produce a report for submission to the director and presentation to the Space Telescope Users Committee (STUC). The results of this study will not only be useful in the near term for Hubble, but can also lay the groundwork for future initiatives with the James Webb Space Telescope.

One factual reference for the forthcoming study is the historical record of the actual performance of planetary proposals in past cycles of Hubble proposal review by the Telescope Allocation Committee (TAC), for which we keep detailed records. While individual proposals remain confidential, the aggregate statistics can be employed to examine the relative success rate for proposals in different disciplines. Here, we present statistics regarding the submission and acceptance of proposals for Solar System science over the past 20 cycles.

**Hubble proposals**

Observing time on Hubble is allocated by the Institute Director based on recommendations made by the TAC. The typical duration of an observing cycle is one year, with separate TACs for each cycle. Most time on Hubble is allocated as General Observer (GO) programs. GO programs are usually executed within a single cycle, but in some cases observations may carry over to future cycles; programs have been terminated if the prime instrument is not available. Snapshot (SNAP) programs are single-orbit observations of a preset target list that are scheduled on an as-available basis in gaps in the GO schedule with no guaranteed completion rate. Director’s Discretionary Time (DDT) is available throughout the year for observations of time-sensitive or high-impact targets. The community can also apply for support for archival research programs or Hubble-related theory programs.

**General Observer (GO) programs**

Table 1 provides statistics on the success rate of GO programs (i.e., regularly scheduled observations) as measured by observing time. Data are presented for all GO programs (columns 2–4) and for Solar System proposals (columns 5–9), although only incomplete data are available for Cycles 1, 2, and 5. The tabulated quantities are described in detail in the table caption. The table includes the TAC allocations for the Multi-Cycle Treasury (MCT) programs; the DDT contributions are listed in Table 5.

Table 1 does not include time allocated to Guaranteed Time Observers (GTOs), who are usually principal investigators of Hubble instruments, for the original Hubble Key Projects, for Pure Parallel programs, for Director’s Discretionary Time, and for the Early Release Observations (EROs) conducted by NASA as an outreach component of every servicing mission.

Large programs, requesting more than 100 orbits, were introduced as a separate category in Cycle 9 to enable the community to tackle larger-scale science programs. Relatively few such programs related to Solar System science have been submitted since their inception. Nevertheless, Table 2 shows that Solar System proposals have been successful at this level: four of the eight proposals submitted since Cycle 11 were allocated time (GO 9433: 116 orbits; GO 10862: 128 orbits; GO 11178: 128 orbits; GO 11644: 120 orbits). Three of those four programs focus on observations of trans-Neptunian objects in the outer Solar System; the fourth provided coordinated observations of Saturn and Jupiter throughout the International Geophysical Year.
In most recent cycles, ~3,800 to 4,000 orbits have been available each year for science observations with Hubble; the exact number depends on how efficiently observations can be scheduled in a given year. Science observations include GTO observations, DDT science programs, and on-sky calibration observations, which, when combined, can account for 600 to 800 orbits, leaving, in principle, about 3,000 to 3,400 orbits for TAC-scheduled GO programs. In practice, the GO orbit totals listed in Table 1 show a wider range of allocations for various reasons.

Scheduling efficiency was relatively low during the first few cycles of Hubble operations, and the lower GO allocations in Cycles 1–3 also take into account a significant GTO allocation.

There were three categories of accepted proposals in Cycles 3 and 4: high priority; medium priority; and supplemental proposals. Supplemental proposals were seldom executed and the accepted totals listed in Table 1 are for the first two categories.

- Cycle 5 was the first cycle to allocate orbits rather than hours.
- Cycle 6 immediately preceded Servicing Mission 2 (SM2) in February 1997, when the Goddard High Resolution Spectrograph (GHRS) and the Faint Object Spectrograph (FOS) were replaced by Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) and the Space Telescope Imaging Spectrograph (STIS).

Table 1: GO orbit allocation statistics, Hubble Cycles 1–20

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Total Requested</th>
<th>Total Allocated</th>
<th>Success Rate R</th>
<th>SS Requested</th>
<th>SS Fraction Requested</th>
<th>SS Allocated</th>
<th>SS Fraction Allocated</th>
<th>SS success rate R(SS)</th>
<th>R(SS)/R</th>
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</thead>
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<td>629</td>
<td>8%</td>
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<td></td>
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<td>1,380</td>
<td>17%</td>
<td>962</td>
<td>15%</td>
<td>172</td>
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<td>40%</td>
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<td>379</td>
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<td>2,920</td>
<td>18%</td>
<td>286</td>
<td>2%</td>
<td>70</td>
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<td>12</td>
<td>19,674</td>
<td>3,150</td>
<td>16%</td>
<td>363</td>
<td>1%</td>
<td>79</td>
<td>3%</td>
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<tr>
<td>13</td>
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<td>4,036</td>
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<td>286</td>
<td>2%</td>
<td>70</td>
<td>2%</td>
<td>24%</td>
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<td>398</td>
<td>3%</td>
<td>220</td>
<td>7%</td>
<td>55%</td>
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<tr>
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<td>545</td>
<td>3%</td>
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<td>63%</td>
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<td>2,578</td>
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<td>94</td>
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<td>2.3</td>
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<td>18,659</td>
<td>2,554</td>
<td>14%</td>
<td>379</td>
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<td>50</td>
<td>2%</td>
<td>13%</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>16,681</td>
<td>2,802</td>
<td>17%</td>
<td>289</td>
<td>2%</td>
<td>84</td>
<td>3%</td>
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<tr>
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<td>343,287</td>
<td>59,551</td>
<td>17%</td>
<td>10,659</td>
<td>3%</td>
<td>3,142</td>
<td>5%</td>
<td>29%</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Notes: Success rates for GO programs as measured by comparing the requested observing time to the allocated observing time are shown. Data are given as orbits, except for cycles 1–4, when time was allocated in hours. Columns 2–4 list submitted and accepted statistics for all GO programs, with column 4 listing the success rate (i.e., the ratio between allocated and requested); column 5 shows the observing time requested for Solar System proposals, and column 6 gives that request as a fraction of the total requested time (excluding Cycle 1); column 7 lists the time allocated to Solar System programs, and column 8 gives that as a fraction of the total time allocated; column 9 lists the success rate for Solar System programs, and column 10 compares the Solar System success rate against the average for all proposals.
Imaging Spectrograph (STIS). The oversubscription was intentional to allow for possible delays in SM2. In the event, SM2 occurred on schedule, and GHRS and FOS programs that were not completed were terminated.

- The Cycle 7 totals do not include statistics for Cycle 7N, the special call for proposals following the identification of the NICMOS dewar anomaly. A total of 415 GO proposals for 6,473 orbits were submitted in response to the call, and 75 proposals for 1,041 orbits were approved. The approved proposals included six Solar System programs for 28 orbits (2.7%). The final duration of Cycle 7 was almost two years.

- The Cycle 16 totals do not include statistics for the contingency and supplementary programs necessitated by the instrument computer (SIC&DH) failure and the postponement of Servicing Mission 4 by eight months. A total of 17 proposals requesting 956 orbits were approved in the supplementary call; three proposals for a total of 151 orbits (16%) were for Solar System science.

- The ~1500 GO orbits allocated to the MCT programs was distributed equally across Cycles 18, 19, and 20, and the TAC GO allocations for Large and Treasury programs are reduced in corresponding fashion for those cycles.

### Table 2: Statistics for Large/Treasury GO Solar System proposals

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Submitted</th>
<th>Accepted</th>
<th>Cycle</th>
<th>Submitted</th>
<th>Accepted</th>
</tr>
</thead>
<tbody>
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<td>2</td>
<td>1</td>
<td>16</td>
<td>2</td>
<td>1</td>
</tr>
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<td>1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>0</td>
<td>18</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>0</td>
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</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: As in Table 1, columns 2–4 list submitted and accepted statistics for all programs, with column 4 listing the success rate (number of targets allocated divided by the number of targets requested); column 5 shows the targets requested for Solar System proposals, and column 6 gives that request as a fraction of the total (column 2); column 7 lists the targets requested to Solar System programs, and column 8 gives that as a fraction of the total SNAP allocation (column 3); finally, column 9 lists the success rate for Solar System programs. Overall, Solar System programs have a higher-than-average success rate and comprise ~7% of all SNAP allocations since Cycle 5.

### Table 3: SNAP allocation statistics, *Hubble* Cycles 5–20

<table>
<thead>
<tr>
<th>Cycle</th>
<th>SNAP Total Requested</th>
<th>SNAP Total Allocated</th>
<th>Success Rate R</th>
<th>SS SNAP Requested</th>
<th>SS SNAP fraction requested</th>
<th>SS SNAP Allocated</th>
<th>SS Fraction Allocated</th>
<th>SS Success Rate R(SS)</th>
<th>R(SS)/R</th>
</tr>
</thead>
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<tr>
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<tr>
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<tr>
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<td>42%</td>
<td>1.8</td>
</tr>
<tr>
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<td>327</td>
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<td>17%</td>
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<td>21%</td>
<td>100%</td>
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<td>3,903</td>
<td>5%</td>
<td>1,633</td>
<td>7%</td>
<td>42%</td>
<td>1.6</td>
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</tbody>
</table>

Notes: As in Table 1, columns 2–4 list submitted and accepted statistics for all programs, with column 4 listing the success rate (number of targets allocated divided by the number of targets requested); column 5 shows the targets requested for Solar System proposals, and column 6 gives that request as a fraction of the total (column 2); column 7 lists the targets requested to Solar System programs, and column 8 gives that as a fraction of the total SNAP allocation (column 3); finally, column 9 lists the success rate for Solar System programs. Overall, Solar System programs have a higher-than-average success rate and comprise ~7% of all SNAP allocations since Cycle 5.
Focusing on Solar System science, the time requested for observations peak both in absolute numbers and proportionately (>8%) in the early Cycles 3–6. Cycles 7 and 8 show a progressive decline in the requested time, and Solar System requests have fluctuated between ~250 and ~600 orbits (1–4% proportionately) in the subsequent 12 cycles. Solar System science received the largest time allocation in Cycle 6, with 420 orbits constituting 9% of the total allocation. Since then, the GO allocations have varied between 2% and 4% of the available orbits in most cycles, with the increased allocations in Cycles 15, 16, and 17, reflecting the success of the Large programs listed in Table 2. With the latter exception, there is no clear evidence that the changes in the TAC process have affected either the demand or the success rate of Solar System GO proposals.

Overall, Solar System science accounts for 3% of the requested time for GO programs over the past 20 cycles. Those proposals have been awarded a total of 5% of the available observing time.

SNAP proposals

SNAP programs are well suited to statistical investigations of a class (or classes) of objects for which a large number of targets are available, all with similar priorities for observation. The overall concept, as originally developed by Rodger Doxsey and John Bahcall, is to make effective use of “dead time” orbits that inevitably arise in scheduling GO programs. The first SNAPs were scheduled in Cycle 1 as a Director’s Discretionary program with the Wide Field/Planetary Camera, and continued in Cycle 2, with targets drawn from a preset list of ~1,000 galaxies and active galactic nuclei. The program was opened to community requests for the full range of astronomical targets in Cycle 3, but observations of moving targets (hence, Solar System objects) were not permitted until Cycle 9.

SNAP programs were created as fillers in the *Hubble* observing schedule, and there is no guaranteed completion rate in observing targets. Programs are terminated after two cycles, and typically 30%–50% of the targets are observed before termination. SNAP proposers are faced with the conundrum that as GO scheduling efficiency increases, SNAP completion rates tend to decline; that is, SNAP programs prosper less as *Hubble* becomes more effective at pursuing its prime programs.

Table 3 compares the success rate for Solar System SNAP proposals against the overall statistics over the last 16 cycles (data are not available for the first four cycles). The columns in this table have the same meaning as in Table 1. The Cycle 7 statistics do not include the Cycle 7N results (8 of 34 SNAP proposals approved for 473 of 3065 targets). Solar System SNAP proposals were not permitted until Cycle 9. Since then, planetary scientists have made extensive use of this opportunity. SNAP programs have proven particularly effective as a means of surveying the properties of asteroids and trans-Neptunian objects (e.g., SNAP 10514, 10800, 11113, 12468 yielded 250, 150, 160, 91 targets; SNAP 9747, 10512 yielded 180, 150 targets). SNAPs have also been deployed as a means of monitoring the atmospheric properties of the outer planets, particularly Uranus and Neptune (e.g., SNAP 11630, 11156: 60, 60 targets).

Overall, Solar System SNAPs account for 7.4% of the total allocated since Cycle 5 and 9.7% of the total since Cycle 9, when the first Solar System SNAP proposal was received. The success rate is 41.8%, almost double that of the average SNAP proposal.

Overall proposal success rates

Tables 1–3 provide a statistical measure of the contribution of Solar System astronomy to *Hubble*’s program as a function of observing time. Table 4 provides information on the success rate of all Solar System proposals reviewed by the TAC, including GO, SNAP, archival and theory programs. The columns of Table 4 follow the same pattern as in Tables 1 and 3, but list proposals, not observing time. Full statistics are not available for Cycle 1. As in Table 1, the Cycle 7 statistics in Table 4 do not include the Cycle 7N (NICMOS) or Cycle 7AR (Archival) call, and the Cycle 16 statistics do not include the Cycle 16 contingency and supplementary programs. Integrating the results from Cycle 2 onwards, Solar System proposals constitute 6.1% of submitted proposals (1,041 out of 16,962 from Cycle 2 to Cycle 20, including the MCT call), and 8.2% of the approved proposals (377 of 4,623).

In recent cycles, the number of Solar System proposals has declined: Cycles 11, 12, and 17–20 all attracted more than 1,000 proposals; Solar System contributed 5–6% of the total in Cycles 11 and 12, but the fraction drops to ~4% post-SM4. Overall, the success rate for Solar System proposals is 36%, that is, more than one in three Solar System proposals submitted has been accepted, which compares with a one-in-four success rate for the overall pool of *Hubble* proposals.

Director’s discretionary time

DDT provides scientists with an opportunity to submit proposals for observing time between meetings of the TAC. In most cases, those proposals are to observe transient phenomena that could not have been predicted at the time of the previous TAC meeting, and will have passed by the next meeting. The proposals are generally sent for peer review to community scientists who served on the appropriate
panels at recent TAC meetings, and who can therefore rank the science proposed in the DDT proposal against recent GO proposals.

Table 5 presents the statistics for DDT proposals. The Institute does not preserve statistics for unsuccessful DDT proposals, so the data presented refer solely to successful programs. The DDT totals include time allocated to the original Hubble Deep Field (HDF; 150 orbits in Cycle 5), the HDF South (193 orbits in Cycle 7), the Ultra Deep Field (400 orbits in Cycle 12) and the Early Release Science (ERS) program allocated to the WFC3 Science Oversight Committee (214 orbits in Cycle 17); DDT contributions to the MCT programs are listed separately.

Solar System astronomy offers a rich tapestry of transient phenomena and consequently is well placed to utilize the DDT proposal mechanism. In particular, the large allocation of DDT in Cycle 4 reflects the concerted program to observe Comet Shoemaker-Levy 9’s impact on Jupiter in July 1994. DDT was also used for follow-up observations of that impact, fortuitously timed just after the completion of SM4. Other proposals have targeted atmospheric activity in comets for imaging and spectroscopic observations, including members of the new class of Main Belt comets.
Summary

Solar System astronomy has been a key part of *Hubble*’s scientific program over the past 20 cycles. Proposal pressure on *Hubble* is high, exceeding 4:1 in most cycles and reaching 6:1 in recent cycles. Solar System GO programs have contributed 3% of the requested time and receiving 5% of the orbits allocated for scientific observations, or approximately one full cycle. The proposal pressure was highest in the earliest cycles, and has remained relatively constant at 2–4% over the past 15 years, from Cycles 8 to 20. Almost 10% of the SNAPs approved since Cycle 9 are for Solar System science, twice the average success rate. Combining all proposal types, Solar System proposals account for 9% of the submitted proposals (GO, SNAP, archival, and theory) and 9% of the accepted proposals since Cycle 5. Thirteen percent of DDT allocated since Cycle 1 has been devoted to observations of Solar System objects.

We will issue a formal call in the near future for community input on optimal approaches to support Solar System research with *Hubble*. In the meantime, the community is reminded that the STUC serves as their representative body, and its members are charged with acting on their behalf. Personally, I welcome comments on this subject or any other topic related to soliciting and allocating observing time on *Hubble* or *Webb*.

Neill Reid is Head of the Institute’s Science Mission Office.

References:

Full details on results for each *Hubble* cycle are included in the *Institute Newsletter*, published after each TAC meeting.

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Notes: Data are given in terms of the time awarded to successful proposals (hours in Cycles 1–4, orbits in subsequent cycles). Approximately 13% of all DDT is awarded for Solar System observing.
Moving On Up—A New Lifetime Position for COS FUV Spectra

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Real estate will tell you that location is everything when buying or selling a house. Location is also paramount in the operation of the Cosmic Origins Spectrograph’s (COS) Far Ultraviolet (FUV) cross-delay line detector. After three years of on-orbit operations, the default location of science spectra taken with the COS FUV channel was changed on July 23, 2012. Since that date, the positions of all external target spectra are shifted upward by about 3.5”, or 41 pixels, on the detector, in a direction orthogonal to the dispersion direction. This move ensures that the spectra obtained with COS will continue to be of the highest quality possible (see Figure 1). Here, we describe the activities that occurred in order to enable and calibrate this new position.

The road to a new lifetime position

From its inception, the design of the COS FUV instrument included a plan for regular moves of the default location of spectra, or “lifetime positions.” This is due to the fact that the cross-delay line detector has a limited amount of charge that can be extracted from any position on the detector. As the cumulative number of photons collected at a given location increases, the total number of electrons generated from the incident photons decreases, leading to a localized loss in sensitivity. This is the so-called “gain sag” effect. When the number of electrons in the charge cloud (the pulse height amplitude, or PHA) drops below a critical threshold, the valid photon events can no longer be recovered. Locations on the detector particularly susceptible to this effect include regions where geocoronal Lyman α airglow lines are located. Sagging in these regions was seen as early as fall 2010, only 1.5 years after the commencement of on-orbit operations. Further investigation revealed that the accumulation of photons from regular usage in external science targets was affecting larger regions of the detector. This motivated a series of exploratory programs designed to specify the next lifetime position.

The final decision on the second lifetime position—a location offset by +3.5” in the cross dispersion direction from the original position—was made in December 2011. Factors influencing the location included the need to maximize spectral resolution, to maintain spectral quality by minimizing the effect of gain sag from previously exposed regions or other detector artifacts, and to extend the amount of time available for operations at the second lifetime position. In the 2012 volume 29, issue 01 of the Institute Newsletter (https://blogs.stsci.edu/newsletter/2012/07/30/a-fresh-start-for-the-cos-fuv-detector/), Oliveira et al. called the exploration for this selection “A Fresh Start for the COS FUV Detector.”

The first “lifetime move,” or change of the default location of spectra on the COS FUV detector, was akin to the activities during the Servicing Mission Observatory Verification (SMOV) in summer/fall 2009, as the performance at the new lifetime position needed to be confirmed. Based on experience with operating the detector on orbit for 3.5 years, a “spot-check” approach was utilized, and other changes to these “mini-SMOV” activities were made based on prior on-orbit experience. The process started before the move by mapping out requirements for programs that would enable science at the new location, and for programs that would provide calibrations to support science at the new location. These activities will be required for every subsequent lifetime move.

Enabling science at the new lifetime position

One of the motivating factors in the choice of the new lifetime position was the ability to remain at this position for an extended length of time—a situation made possible due to successive increases of the high-voltage value—because increasing the voltage augments the number of electrons in the charge cloud, temporarily ameliorating any effect of gain sag. Due to operational restrictions, there is an upper limit to the high-voltage value, which limits the possible number of voltage increases.

The first enabling science activity involved determining the beginning value of high voltage, in order to extend the lifetime while maintaining high data quality. To do this, we performed a high-voltage sweep and examined the distribution of PHAs at each voltage, as well as the data quality. The decision was made to start operations at a voltage corresponding to a modal PHA of 10. Coupled with voltage increases every six months to one year, this will allow for approximately five years of operations at the second lifetime position without any major loss of data.
Figure 1: The top panel shows the locations where photons have fallen on the COS FUV detector from launch in May 2009 until March 2013. Prior to July 23, 2012, most counts were collected at the original lifetime position, near the middle of the detector. After this date, the default location or lifetime position changed to expose fresh regions of the detector; this new location is offset by about 41 pixels upward from the original lifetime position. The locations of wavelength calibration spectra lie above these regions. The bottom panel compares two G130M/1327 spectra of the white dwarf WD0947+857 at the two lifetime positions, and shows the improvement in spectral quality realized by this lifetime move. The black curve is the spectrum obtained as one of the last exposures at the original lifetime position; the hatched regions show several gain-sag holes in the spectrum, while these are absent in the spectrum taken at the second lifetime position in red. A real feature in the spectrum, the S ii absorption line at 1253 Å, is also recovered.
The high-voltage sweep activity also explored the dependence of the measured photon position on the PHA. The position of events with low PHA can be misregistered due to detector electronics; determining their starting position is the so-called “walk correction” described in Sahnow et al. (COS ISR 2011-05; http://www.stsci.edu/hst/cos/documents/isrs/ISR2011_05.pdf). At the initial lifetime position, a linear walk correction in the Y direction was implemented after the effect had become apparent in the data; this formulation was the best available at the time. Part of the high-voltage sweep activity included a characterization of the walk using a series of internal wavelength calibration lamp images at a variety of voltages. Examination of the data shows that the Y walk behavior is more complicated than the linear function described earlier, but appears to be independent of detector Y location. This improved walk correction can be applied to all data taken, regardless of the lifetime position. Variations of the line centroids in the dispersion direction due to detector walk effects (“X walk”) were systematically examined for the first time in this program, and shown to be significant for events with low PHA values (see figure). The X walk varies with position across the dispersion direction of the detector, but does not appear to vary with Y location, so it can be applied to all lifetime positions. X walk is not currently included in pipeline reductions, and may affect the spectral resolution of data with PHA values below five, as the figure demonstrates. Reference files implementing these corrections will be delivered in spring 2013.

While the activities in the exploratory programs constrained where the second lifetime position should be, observations in the enabling phase verified that the spectrum placement was as expected. Due to variations in the local plate scale over the detector from the initial lifetime position to the second one, the initial shift did not displace the spectra far enough to completely avoid the previously sagged regions. The 3.5" offset from the original lifetime position was placed at 41 pixels to maximize the margin for pointing errors while still meeting the spectral resolution requirements. External target observations also confirmed the aperture centering by stepping the aperture by positive and negative values both along the dispersion and across the dispersion direction, holding the target position fixed. One result was the need to change the aperture pointing by –0.05" in the dispersion direction so that targets are centered in the aperture. These results are transparent to users and were implemented before the next series of enabling programs.

The third enabling activity was a focus sweep for each grating to determine the optimal focus value to maximize spectral resolution. Because the FUV channel on COS does not have any imaging capability, the focus can only be confirmed by using targets with narrow absorption lines. A series of ray-trace models run to predict the best focus at the second lifetime position showed that the optimum focus should lie within 0–200 focus steps of the best focus at the original position. Focus sweeps were performed for each grating near these predicted best-focus values, and as expected the foci for all gratings moved by roughly the same amount. The best focus for the G140L grating is strongly wavelength dependent and the focus curve is strongly asymmetric; the focus value was the minimum of the sampled points and is optimized for the 1250–1350 Å region.

The final enabling activity consisted of a set of observations to update the parameters used for FUV target acquisition. A series of tests verified that the ACQ/SEARCH, ACQ/PEAKD, and ACQ/PEAKXD target acquisition algorithms work at the second lifetime position by determining parameter updates such as subarrays of the spectrum used to perform target acquisitions. With these tests completed, the switch to operations at the second lifetime position took place on July 23, 2012. The final visit of this enabling program, a full target acquisition sequence (ACQ/SEARCH+ACQ/PEAKXD+ACQ/PEAKD) and a short target acquisition sequence (ACQ/PEAKXD+ACQ/PEAKD), was the first COS dataset taken after the switch. With this final verification, the team confirmed that routine operations of the COS FUV channel at the second lifetime position could proceed without incident.

**Lifetime calibration activities after the lifetime move**

The performance of the COS FUV channel at the original lifetime position was confirmed during an exhaustive series of tests during SMOV in 2009 and has been monitored through regular calibrations during Cycles 17–20. While no major changes were expected to occur as the result of the lifetime move, a series of lifetime calibration activities took place as a spot check of the performance. Every attempt was made to minimize the number of exposures needed to perform these activities, and the team made use of considerable synergies in overlapping requirements for programs to do this.

Data from exploratory programs and ray-tracing models had predicted that the spectral resolution at the second lifetime position should be within 15% of the spectral resolution at the original lifetime position. The predicted change in the wavelength-dependent line spread function (LSF) was thus expected to be small. Observations of a bright external target with unblended optically thin and partially optically thick absorption lines confirmed the spectral quality of the data. Figure 3 confirms that the spectral resolution is within 10–15% of the resolution at the original lifetime position. Given the small change, the LSF at the original position will suffice for most analyses. The computation of new theoretical LSFs at the second lifetime position (including mid-frequency wave front errors and scattering wings) is being finalized and these will be made available to the community in spring 2013.
Figure 2: Illustration of the magnitude of X walk on detector segment FUVA (top two panels) and FUVB (bottom two panels). Images of the same wavelength calibration line were obtained at a variety of voltages, and the X centroid versus pulse height is plotted. The left panels illustrate behavior on the left edge of the respective detector segment, while right panels show trends from wavelength calibration lamp lines on the right edge of the detector segment. A new X walk correction and updated Y walk correction are being implemented in the CALCOS pipeline, and will be applied to all data taken, regardless of lifetime position.

The same external target exposures used to verify the spectral resolution also confirmed the wavelength scale at the second lifetime position. The difference between positions of absorption lines measured in extreme central wavelengths was generally less than 3 pixels, or half a resolution element. This was the expectation based on comparison of spectra taken during ground testing, SMOV, and routine wavelength scale monitoring in prior calibration cycles. This activity demonstrated that the wavelength solution does not vary appreciably at the second lifetime position compared to the first lifetime position, as expected, and there is no need to update the dispersion solutions. Additionally, the observations carry over the wavelength scale monitoring at the second lifetime position with a new target. Since the requirements for the wavelength verification program are similar to the program designed to confirm the spectral resolution at the new lifetime position, no additional exposures were needed.

The flux calibration at the new lifetime position proceeded in concert with determinations of flat-field variations. Observations of DB white dwarf spectrophotometric stars enabled the flux calibrations of all grating modes. The absence of lines in the UV (particularly Lyman $\alpha$) and the flatter spectral energy distribution make these targets more ideal for flux calibration purposes than the DA white dwarfs used previously. The observations for flux and flat-field calibrations were driven by the need to characterize the flat-field variations at the new lifetime position. As expected, the absolute flux calibration shows little change (less than few percent) from the sensitivity at the original lifetime position after the effects of flat-field variations and slight differences in the high-voltage values are taken into account. At the original lifetime position, low order flat-field variations in sensitivity on the order of 10% across the detector had been characterized, and these were confirmed to occur at the second lifetime position also (Figure 4). These low order variations occur across the dispersion direction of the detector; together with the locations of grid-wire shadows, which can cause up to 20% local decrease in flux, they are
Figure 3: The top plot compares the line spread function (LSF) computed for the original lifetime position (LP1, dashed line) with the line spread functions computed at the second lifetime position at a number of wavelengths, for the COS G130M 1291 setting. The LSFs computed for the second lifetime position include the effect of scattering wings. The differences occur mainly near the peak and are 10–15% in magnitude. The bottom plot compares an absorption line in the spectrum of AzV 75 obtained with STIS (black line), COS in the G130M/1291 setting (purple line) and G130M/1327 setting (red line). The green and blue lines show the STIS spectrum convolved with the COS LSF appropriate for that setting. Below the spectra are the residuals between the observed COS flux densities and the modeled values.
confirmed to be roughly independent of lifetime position. These are being combined into a reference file for delivery in spring 2013. Variations in the pixel-to-pixel sensitivity response have also been determined; as expected, these do depend sensitively on detector lifetime position and the timescale for implementing these is longer.

A final calibration activity confirmed the ability to obtain FUV spectra through the Bright Object Aperture (BOA) at the second lifetime position. This mode had not been used since SMOV, and spatial profiles and spectral resolution appear to have improved slightly. This activity also verified the use of auto-wavecals for wavelength calibration at the second lifetime position.

Figure 4: The top panel illustrates the 10% amplitude sensitivity variations across the FUVA detector and smaller variations across the FUVB detector. The middle panel shows spectra from the G130M grating on the FUVA detector taken at widely separated central wavelengths. The effect of the uncorrected large-scale sensitivity variations is evident. The bottom panel shows the same spectra after correction by the L-flat at top.
Impact of calibrations on the lifetime at the new position

The new lifetime position started off as a relatively pristine piece of real estate on the detector, having had little to no photon accumulation in the previous 3.5 years of on-orbit operations. Because gain sag occurs as the result of photon accumulation, and the calibration activities here use bright targets for calibration purposes, the number of photons collected was monitored carefully. Experience with gain sag at the original lifetime position showed that once approximately $2.7 \times 10^4$ photons are collected in one detector element, or pixel, the decrease in the pulse height amplitude distribution of events falling in that pixel leads to a 5% loss in throughput. Predictions of the maximum and average number of photons which might fall on a pixel due to the detector configurations and exposure times used in lifetime calibration programs gauged the impact of these calibrations on detector lifetime. Post hoc inspection of the number of photons collected for all enabling and calibration programs showed that the typical pixel accumulated less than 200 photons during these activities, and the pixels receiving the most light are still well below the level at which sensitivity loss might occur as a result of these activities.

Impacts for observers

Since the first lifetime move occurred on July 23, 2012, spectra are routinely taken at the second lifetime position on the COS FUV detector. The switch affects only a few calibration reference files. The spectral extraction regions were updated prior to the lifetime move, to ensure that the pipeline correctly locates the wavelength calibration spectrum and extracts the science spectrum at the appropriate position. The absolute flux calibration reference file is being delivered with a dependence on lifetime position. LSFs appropriate for the new lifetime position, and including the effects of mid-frequency wave front errors and scattering wings, will be available for the community to use in modeling spectra.

Observations taken as part of the enabling and calibration phases of the lifetime move are improving calibrations at all lifetime positions. A new bad-pixel map for a larger region of the detector was delivered based on the exploratory programs, and regions affected by gain sag will be updated regularly. The flat-field reference file, consisting of the large scale sensitivity variations and grid-wire shadowing of external spectra, is being delivered with improved characterization for both lifetime positions. The improved flat-field characterization will lead to an improved flux calibration at the original lifetime position. An improved walk correction in the across dispersion direction is being implemented, and a new correction in the dispersion direction is in progress; these can be applied to data taken at all lifetime positions. At present there are no plans for simultaneous operations at more than one lifetime position. The lifetime enabling and calibration activities described in this article will need to be repeated with each lifetime move, updated by future experiences operating COS. We expect that the next lifetime move should not need to occur for approximately four years.

The Unique Coronagraphic Capabilities of STIS: Direct Imaging

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Spatially resolving circumstellar disks and directly detecting exoplanets in close proximity to stars requires extreme suppression of starlight: the light from such objects ranges from less than one part per billion up to a few hundred parts per million of the light from their host star. Directly imaging faint objects close to bright stars requires the ability to subtract or suppress the diffracted light from the central star. As a class, these techniques are called “high-contrast” observing.

Despite having been in space over 16 years so far, the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope still offers high-contrast imaging and spectroscopy not possible with any other current Hubble instrument—nor with any current or future ground-based adaptive-optics coronagraph. STIS’s coronagraph, or imaging mask, can suppress stray unwanted light from bright sources to reveal faint structures and discover sources at close angular proximity.
Since its repair during Servicing Mission 4, STIS has broken new ground in imaging scattered visible light from circumstellar dust in exoplanetary debris systems (Schneider et al. 2013), elucidating the orbit and nature of the enigmatic planetary candidate Fomalhaut b (Kalas et al. 2013; Currie et al. 2012), and discovering new, faint debris disks, which may host planetary systems (Krist et al. 2012).

Two capabilities of STIS are particularly noteworthy: imaging with exquisite contrast—about three hundred parts per million at apparent separations as small as 0.4" and about one part per million at 1"—and coronagraphic spectroscopy over visible wavelengths at similar contrasts. In this article, we discuss the general strategies for coronagraphic imaging, and describe a *Hubble* program that has made use of these techniques.

**High contrast at small separations**

STIS was not primarily designed as a coronagraphic instrument. Its mask, which is rather simple, is a combination of image-plane wedges, which can be used to block the light from a central star (see Figure 1). Typically, coronagraphs also actively suppress light from a star’s Airy disk, using a Lyot stop in the pupil plane. In addition, STIS coronagraphy relies on reference stars to subtract any residual diffracted light that passes the coronagraphic wedges.

Two of the supported, vertical, wedge positions in the STIS coronagraphic aperture are where the wedge is 1" (the WEDGEA1.0 position) or 0.6" wide (the WEDGEA0.6 position). To obtain high contrast at small separations requires imaging the target at the WEDGEA0.6 position. Because of the wedge structure, obtaining high contrast at 0.3" for all azimuthal angles around the occulted star requires imaging the target at six separate spacecraft rolls. *Hubble* can typically support rolls up ±30° from a nominal orientation at any given time, primarily limited by an acceptable angle between the solar arrays and the Sun.

Program GO 12228 (PI: G. Schneider) pioneered an effective observing strategy involving observations at roll angles –30°, 0°, and +30° offset from the nominal spacecraft orientation. These observations were followed by three more orientations at a later epoch, where the nominal spacecraft orientations were 90° and 150° offset from the first set of observations (see Figure 2). This strategy effectively achieves full azimuthal coverage as well as good mitigation of systematic residuals in light subtraction, which often are significantly larger than the photon-noise limit. For more compact structures, such as an edge-on disk, one can observe with fewer rolls (e.g., Krist et al. 2012), but with the penalty of larger residuals.

The GO 12228 program took short exposures of the targets at WEDGEA0.6 followed by much deeper exposures at WEDGEA1.0. This program was designed to image the scattered light from debris disks at orbital distances of a few AU and extending out to the most tenuous regions of the disk, at hundreds of AU.

To allow the subtraction of the remaining starlight exterior to the wedges, the GO 12228 program also imaged a reference star at both wedge positions. For such operations, it is imperative to choose the reference star carefully. Best subtraction results come from a star with a closely similar spectral energy distribution over the broad bandpass of STIS. The instrument has significant throughput in the range 2000–10,000 Å, and typically the similarity requirement is to keep both $|\Delta(\beta-V)|$ and $|\Delta(V-R)|$ less than 0.1, where $\Delta$ indicates the color difference between the target star and reference star. Additionally, selecting a reference star nearby on the sky, and observing it close in time to the science observations, reduces systematic errors.

Figure 1: Full STIS coronagraphic aperture including two wedges, a wide bar, and a coronagraphic finger (which was bent during the assembly of the instrument). The lower white square represents the WEDGEA0.6 position while the upper white square represents the WEDGEA1.0 position. For a full listing of all supported positions, see [http://www.stsci.edu/hst/stis/documents/handbooks/currentIHB/c12_special12.html](http://www.stsci.edu/hst/stis/documents/handbooks/currentIHB/c12_special12.html). Credit: John Debes.
Figure 2: Visualization of masked areas in the image plane for various combinations of spacecraft rolls, at WEDGEA0.6. For a typical single visit (upper-left panel), the wedges and diffraction spikes from an occulted star are masked out, which obscures certain azimuthal angles. Regions that are never imaged are black, while various levels of grayscale correspond to partial coverage of an azimuthal position. A total of six separate spacecraft orientations can provide near-complete azimuthal coverage and significant suppression of the residuals after subtracting the reference star. Credit: Marshall Perrin.

in the subtraction. These steps minimize the effects on the subtractions from temporal variations in Hubble’s optical wavefront.

The results for one of the targets in the GO 12228 program, HD 181327, are presented in Figure 3. At a distance of 52 pc, the 0.3" angular limit corresponds to a distance of 16 AU. These observations achieved a contrast relative to the star of \(-3 \times 10^{-4}\) per STIS resolution element at an apparent separation of 0.4".

An alternative approach, best suited for sharp structures or point sources, would be to use optimized subtraction algorithms, such as the Locally Optimized Combination of Images (LOCI) algorithm (Lafreniere et al. 2007) or the Karhunen-Loeve Image Projection (KLIP) algorithm (Soummer, Pueyo, & Larkin 2012). These algorithms are efficient at suppressing scattered starlight, but they require large libraries of reference stars, covering the range of point-spread functions associated with wavefront variations, for a space telescope, or, for ground-based AO observing, quasi-static features due to thermal or mechanical deformations of telescope optics during long exposures. For example, a library of NICMOS PSFs was delivered to the Institute archive by AR/11297 (G. Schneider, PI). KLIP in particular has been shown to effectively detect debris disks and faint point sources in other Hubble observations with NICMOS. Unfortunately, a dedicated reference star library does not exist for STIS. In the case of GO 12228, the faint and diffuse extended structures beyond 1" observed in Figure 2 for HD 181327 are currently challenging for LOCI or KLIP to detect. Further work needs to be done to determine an optimized strategy for using LOCI or KLIP with STIS.

STIS provides unparalleled performance for high-contrast observations of nearby debris disks in scattered light at optical wavelengths. The best results call for optimizing both the use of the coronagraphic wedges and the selection of reference stars.
The old adage, “a picture is worth a thousand words,” could not be more appropriate for the Hubble Space Telescope and its inspiring and breathtaking images. However, as a well-known spectroscopist told his students, “You can’t do astrophysics just by taking images through little colored pieces of glass!” He was pointing out the complementary powers of other observational approaches, particularly spectroscopy, and the many uses made of Hubble’s unique spectroscopic capabilities amply illustrate his point.

In order to advance the scientific benefits of Hubble’s spectroscopic capabilities, the Institute organized and hosted a workshop entitled “Enhancing the Legacy of HST Spectroscopy,” on November 15–16, 2012. It attracted nearly 70 participants, who represented the worldwide community of astronomers using medium- and high-resolution—mostly ultraviolet—spectroscopy with Hubble, primarily with the active instruments. The goal of the workshop was to explore ways to optimize the impact of Hubble spectroscopy on current and future research, including both direct and archival investigations.

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Enhancing the Legacy of Hubble Spectroscopy

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The old adage, “a picture is worth a thousand words,” could not be more appropriate for the Hubble Space Telescope and its inspiring and breathtaking images. However, as a well-known spectroscopist told his students, “You can’t do astrophysics just by taking images through little colored pieces of glass!” He was pointing out the complementary powers of other observational approaches, particularly spectroscopy, and the many uses made of Hubble’s unique spectroscopic capabilities amply illustrate his point.

In order to advance the scientific benefits of Hubble’s spectroscopic capabilities, the Institute organized and hosted a workshop entitled “Enhancing the Legacy of HST Spectroscopy,” on November 15–16, 2012. It attracted nearly 70 participants, who represented the worldwide community of astronomers using medium- and high-resolution—mostly ultraviolet—spectroscopy with Hubble, primarily with the active instruments. The goal of the workshop was to explore ways to optimize the impact of Hubble spectroscopy on current and future research, including both direct and archival investigations.
The workshop was a stimulating mix of technical and scientific, invited and contributed talks, demos, and brainstorming sessions and commentary.

The invited talks addressed a variety of subjects. The opening talk was an introduction to Hubble spectroscopy, which was followed by an update on the special capabilities of Hubble’s two operating spectrographs—the Cosmic Origins Spectrograph (COS) and the Space Telescope Imaging Spectrograph (STIS). Optimal techniques for combining Hubble spectral data, including presentations and demonstrations of the spectroscopic products and tools in the Virtual Observatory (VO) and the Hubble Legacy Archive (HLA) received special attention. (See Figures 1–2.)

Although the workshop was primarily data-oriented, it included a series of invited scientific talks on current astrophysical topics. These talks spanned the range from exoplanets and stellar debris disks, to hot and cool stars, to interstellar medium (ISM), circumgalactic medium (CGM), and intergalactic medium (IGM), to active galactic nuclei (AGNs). See Figures 3–4 for some interesting recent results.

The synoptic view offered by these talks provides a basis for the Institute to plan the future evolution of spectroscopic observing capabilities, data processing, analysis tools, and archival data—all services which the Hubble mission provides to the broad community of spectroscopists. These talks also served as the introduction to a brainstorming session on the completeness of the Hubble archive, including possible areas where future observations would improve archival science.

The workshop’s splinter sessions focused on a few scientific topics—AGNs, IGM, stars, ISM, exoplanets—to identify key, must-do observations that the community would greatly regret not having performed if Hubble were to cease operations. These splinter sessions were timely in light of the new “UV Initiative” in Cycle 21, which is aimed at capitalizing on Hubble’s unique UV spectroscopic and imaging capabilities.

A panel discussion at the workshop addressed the issue of which tools users need to locate spectroscopic data products in the Hubble archive, and how the Institute and the astronomical community at large can meet these needs. Some of the most experienced users of Hubble spectroscopic data
Figure 2: View of the spectrum of HD 104705, a blue supergiant in the constellation Crux, through the zoomable interactive display recently implemented in the HLA. The display facilitates quick-look capabilities for archival research. Users will typically use such information to determine whether the data satisfy the needs of their project; downloading is the next step. The spectrum shown here was originally obtained by Ken Sembach and collaborators for Hubble program GO 7270. Tom Ayres recently reprocessed the spectrum as a high-level product and delivered it to the HLA as part of the STARCAT spectral library.

**Figure 3:** Distant quasars serve as remote lighthouse beacons that shine through the gas-rich “fog” of hot plasma encircling galaxies. At UV wavelengths, COS is sensitive to absorption from many ionized heavy elements, such as nitrogen, oxygen, and neon. COS’s high sensitivity allows us to study the many galaxies that lie in front of the much-more-distant quasars. The ionized heavy elements serve as proxies for estimating how much mass is in a galaxy’s halo. Illustration credit: NASA, ESA, and A. Feld (STScI); science credit: NASA, ESA, N. Lehner (University of Notre Dame), T. Tripp (University of Massachusetts, Amherst), and J. Tumlinson (STScI). (STScI-2011-37, released November 11, 2011.)
followed this discussion with several specific technical talks, providing input on processing, data analysis tools, archival products, and interfaces for spectra obtained by Hubble. Ultimately, the purpose is to facilitate the use of spectroscopic data by General Observers and archival researchers.

A closing roundtable discussion addressed the requirements and design considerations for a general processing spectroscopic pipeline to produce high-level archival products by combining data taken at different wavelengths, with different Hubble spectrographs, as well as spectrographs from other space- and ground-based facilities.

In light of the timely and relevant feedback collected during the workshop, the Institute organized a working group to look into the implementation of some of the higher-priority items, including: improvements to Hubble’s spectroscopic products; creation of new products; access to these products via the archive; and more systematic inclusion of Hubble data in meta-catalogs. We expect to start working on some of these items over the summer of 2013.

All of the Workshop presentations have been webcast and archived at this web site: https://webcast.stsci.edu/webcast/searchresults.xhtml?searchtype=20&eventid=183&sortmode=1
Hubble Constant: Building a Better Distance Ladder

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To measure distances across the vastness of space, astronomers often build distance “ladders” using nearer and more common objects to determine the distance to objects that are more rare and distant. At 100 Mpc and beyond, the ladder can be used to measure the Hubble constant ($H_0$) which quantifies the expansion rate of the universe. A precision approaching 1% for $H_0$ would be invaluable to help address important cosmic mysteries, such as the history of cosmic expansion, the nature of dark energy, and the general curvature of space. High precision in $H_0$ is also needed to mount a cosmological challenge to the Standard Model of basic physics through derived constraints on cosmic neutrinos, and to frame the grand inventory of the cosmic objects gathered by Hubble Space Telescope and James Webb Space Telescope, which will extend back in time to the era of reionization.

The centerfold illustrates improving precision and accuracy of the measurement of $H_0$. The top two science objectives listed in NASA’s 1977 Announcement of Opportunity (AO) for the Hubble Space Telescope were “Precise determination of distances to galaxies out to expansion velocities $\sim 10^4$ km s$^{-1}$ and calibration of distance criteria applicable at cosmologically significant distances,” and “Determination of the rate of the deceleration of the Hubble expansion of the universe, its uniformity in different directions, and possibly its constancy with time.” One could say that Hubble was chartered from the outset to measure cosmic distances, particularly by finding and measuring distances with Cepheid variable stars in remote galaxies. Making qualitative advances would demand the superb photometric sensitivity and spatial resolution available only in space.

In Hubble’s first decade, its Wide Field and Planetary Camera 2 (WFPC2) was used to resolve Cepheids in hosts out to 20 Mpc to calibrate longer-range distance indicators such as type Ia supernovae, the Tully-Fisher relation, and the luminosity function of planetary nebulae. From ground-based telescopes, Cepheids are also readily visible in the Large Magellanic Cloud (LMC), our dwarf neighbor 50 Kpc away, where their importance was first discovered by Henrietta Leavitt 100 years ago. This “Cepheid rung” completed a new distance ladder, resolving the existing factor-of-two uncertainty in $H_0$ by measuring it to 10% precision. This true landmark in cosmology was achieved by two groups of astronomers—the Key Project team led by Wendy Freedman (Freedman et al. 2001) and the Sandage consortium led by Alan Sandage (Sandage et al. 2006). The residual 10% uncertainty in $H_0$ in the 1990s was due in part to systematic uncertainties along the ladder. For example, at optical wavelengths, the luminosity of Cepheids depends on metallicity. The LMC is metal-poor and the Galaxy—as well as distant spiral galaxies—are metal-rich. To account for this difference, the Cepheid luminosities had to be corrected for their metallicity, and the greater the difference, the larger and more uncertain the correction. A challenge for future reduction of error was that shorter-period Cepheids are more common, but in more distant galaxies only the longer-period, brighter Cepheids can be seen, thus producing another correction—and its uncertainty from the mismatch in period between the Cepheids in the LMC and more distant galaxies. Another limitation was posed by the small volume in which WFPC2 could find and measure Cepheids—a sphere of only ~20 Mpc radius—which limited the number of rare SN Ia events in that volume to about one per decade. To improve statistics, astronomers needed to take advantage of a few SNe Ia recorded years ago on photographic plates or with high extinction, which required understanding the properties of analog data (Pierce and Jacoby 1995), the form of extragalactic extinction laws, and the differences in the zero points of flux for ground-based photometry and WFPC2 photometry.

After the installation of new Hubble instruments—Advanced Camera for Surveys (ACS), Near Infrared Camera and Multi-Object Spectrometer (NICMOS), and Wide Field Camera 3 (WFC3)—the SHOES (“Supernovae, $H_0$, for the Equation of State of dark energy”) team led by Riess and Lucas Macri constructed a new pair of Cepheid rungs between NGC 4258, the maser host 7 Mpc away, with a geometric distance good to 3% by Humphreys et al. (2008, 2013), and the hosts of recent SNe Ia observed with CCDs to 40 Mpc. These new rungs reduced systematic errors of the prior by acquiring Cepheids of similar metallicity and period in both sets and by observing both with the same camera to eliminate the use of uncertain flux zero points. In addition, the Cepheids were all observed in the near infrared (NIR) to mitigate the effect on Cepheid fluxes of variations in host dust and chemistry. The factor of eight increase in volume reached by the new rung provided a sample of eight recent, nearby SNe Ia with the same high-quality CCD photometry used to measure the expanding universe to a few Gpc, about 25 times farther than other secondary distance indicators. The SHOES team reached a 5% uncertainty using ACS and NICMOS in 2009 (Riess et al. 2009), and just over 3% with WFC3 in 2011 (Riess et al. 2011).
Hubble Constant

Building a Better Distance Ladder

10% Error

Key Project & Historic SNe Ia

1990s

Measure:
- Hubble flow with Recent SNe Ia (D to 400 Mpc)
- Tully-Fisher & Other Galaxy-based Distance Indicators (D to 100 Mpc)

Supernova Change:
- Photographic to CCD Zero-points

Measure:
- Cepheids
- Nearby Galaxies (D < 20 Mpc)
- Tully-Fisher, Ground
- Historic, Photographic SNe Ia, Ground

3% Error

Supernovae & NIR Cepheids

2000s

Measure:
- Hubble flow with Recent SNe Ia, Optical (D to 3 Gpc)

Measure:
- Cepheids in SNe Ia Hosts, Half-a-dozen (D < 40 Mpc)
- Recent SNe Ia, Optical, Ground

~1% Error

Precision Astrometry

2010s

Measure:
- Hubble flow with Recent SNe Ia, NIR (D to 6 Gpc)

Measure:
- Cepheids in SNe Ia Hosts, Complete Sample (D < 40 Mpc)
- Recent SNe Ia, NIR, Ground
Yet, just as the 2000s ladder was being completed, a third, more powerful ladder, enabled by high-precision astrometry, had begun construction.

Trigonometric parallaxes to Cepheids in the Milky Way can, in principle, enable a distance ladder to reach 1% precision. Using the Fine Guidance Sensors on Hubble, the Astrometry Science Team, led by Fritz Benedict, pioneered this effort by measuring the parallaxes of the 10 nearest Cepheids all within 0.5 Kpc (nine with short periods) to a mean error of 3% (Benedict et al. 2007). The SHOES team used NIR observations of this sample to provide an alternative anchor to the 2000s ladder (Riess et al. 2011) and Freedman et al. (2012) used optical observations of this sample for a better start to the earlier, 1990s Key Project ladder.

To maintain the high level of precision across the distance ladder, Cepheids with high-quality parallax measurements in the Milky Way must ultimately have similar long periods and should be observed with the same, NIR or FIR instrument as those in the far Cepheid rung. A new Hubble capability—spatial scanning with WFC3—can provide the needed flux measurements of the bright Cepheids with little or no saturation and simultaneously measure their parallaxes. An ambitious effort by Riess, Stefano Casertano, and the SHOES team has begun in Hubble Cycle 20. The plan is to use the enhanced sampling of spatial scanning with WFC3 to achieve an astrometric precision of 40 microarcseconds, which will enable measuring the parallaxes of the less common, but crucial, longer-period Cepheids, which live between 1 to 3 Kpc. By the end of this decade, the ESA Gaia mission is expected to deliver precise Cepheid parallaxes out to 10 Kpc.

The improvements gained in the use of secondary distance indicators between the 1990s and 2000s ladders must be retained and extended to achieve the goal of 1% precision for $H_0$ for the 2010s ladder. Additional precision can come from the use of SN Ia NIR light curves, which show even lower scatter than in the optical. To reach 1%, the sample size of the nearer SNe Ia must be expanded to more than 25 objects, which will happen by luck, persistence, and, when it is commissioned, the extended reach of Webb. The SHOES team already has a program in place to double the present sample, to 16 SNe Ia, in Cycle 20.

When this new ladder is completed during Hubble’s third and likely final decade, it will be a powerful tool, sharp enough for probing the remaining mysteries of the cosmological model.

References
Notes from the WFC3 Team

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The Wide Field Camera 3 (WFC3) continues to operate nominally and produce lots of science. The WFC3 team is pleased to report that the total number of in-flight exposures (including external and internal science, and calibration exposures) passed 100,000 as of 0814UT on April 23, 2013. The milestone image of CLJ1226+3332 was taken as part of Marc Postman’s CLASH program. Fittingly, this was a F275W ultraviolet image.

Last summer, we commissioned a capability to perform a post-flash to reduce the impact of accumulated radiation damage in the charge-coupled device (CCD) sensors in the ultraviolet-visible (UVIS) channel. This post-flash has now been widely adopted by observers. It is meant to compensate for the radiation-induced decline in charge-transfer efficiency (CTE), which is most significant for exposures with low backgrounds (i.e., with ultraviolet or narrow filters). Due to the very low readout noise in the UVIS detectors, CTE decline had become a limiting factor for many observations. For observations with low background, inclusion of a post-flash to elevate the background signal level to ~12 electrons produces less trailing of charge and, most importantly, improves the detection of very faint sources.

In mid-March 2013, the Institute released a preliminary version of a tool in the post-observation software to further correct for charge trailing in CCD images. While it is most effective when used in combination with a post-flash, this tool is also suitable for correcting any UVIS observation. More information is available at http://www.stsci.edu/hst/wfc3 under “Performance/CTE” and “Software Tools/CTE Tools.” The WFC3 team would particularly appreciate user feedback on this tool. We plan to continue to experiment and evolve the algorithms and calibration for the new tool to correct charge

Figure 1: Hubble WFC3 and ACS images of 30 Doradus are combined with ground-based data of the Tarantula Nebula, taken with the European Southern Observatory’s 2.2-meter telescope in La Silla, Chile. NASA and the Space Telescope Science Institute released the image to celebrate Hubble’s 22nd anniversary. Image credit: NASA/ESA/D. Lennon (ESA/STScI).
Our goal is to incorporate it into the calibration pipeline in 2014. We expect to implement an architecture similar to the one in place for the Advanced Camera for Surveys, with products available that are both corrected and uncorrected for CTE decline.

Other interesting news from WFC3 includes the increasing use of spatial scans. In this technique, the telescope is moved during the observation, so the light from each source is spread over many pixels in an organized fashion. These spatial scans enable new classes of observations that were previously impossible. The applications include: recording the transits of exoplanets, precision photometry of very bright sources, relative astrometry with precision approaching 30 micro-arcseconds, and efficient validation and improvement of flat-field calibrations.

For exoplanet transits, combining spatial scans with infrared (IR) spectroscopy offers three advantages: averaging over many pixels, access to brighter targets, and improved ratio of photon-collection time to data-readout time. Taking the concept of brighter targets to an extreme, we have used spatial scans to successfully observe Vega—one of the brightest stars in the sky and a fundamental calibration source. In these observations, IR grisms dispersed the light, and the minus-one spectroscopic order of the grisms was used to achieve an additional factor of ~80 in brightness reduction.

General Observers are using spatial scans to observe bright, nearby Cepheid variable stars to improve our knowledge of the Hubble Constant. That work, by Adam Riess and collaborators, also uses spatial scans to measure the parallaxes of these Cepheids out to distances three—four times greater than what was previously possible with Hubble’s Fine Guidance Sensors. Now, long scans on the UVIS detector can measure the separation between two stars to a precision approaching 30 micro-arcseconds. Nevertheless, precision astrometry with spatial scans poses calibration issues, for example as regards local plate-scale distortions.

Finally, we have used spatial scans to move a star around on the CCD detectors in a zig-zag pattern, which allows us to measure the quality of the current flat-field calibrations and, potentially, to improve those calibrations at mid-spatial frequencies.

To support Cycle 21 observers, we have enhanced the ASTRONOMER PROPOSAL TOOL to support visualization of spatial-scan patterns on the sky. In other software improvements, the WFC3 team is working closely with the Institute’s Science Software Branch to improve two key pieces of code for the calibration of WFC3 data. First, the WFC3 calibration pipeline is now available for download in an “IRAF-free” version at (see HSTCAL at http://www.stsci.edu/institute/software_hardware/stsdas/download-stsdas). This is the same code used in the Institute pipeline. It is now available both as a stand-alone executable and for use with the various PYTHON environments.

Second, we have been involved in the development, testing, documentation, and user support of ASTRODRIZZLE/DRIZZLEPAC. In conjunction with ASTRODRIZZLE development, we are exploring improvements to the calibration of the WFC3 UVIS channel.

Our goal is to improve the current 0.1 pixel relative astrometric accuracy to 0.05 pixels, while removing the medium scale structure in the CCDs. Please send any information or suggestions about these software tools—or any other aspects of WFC3 operations and calibration—to help@stsci.edu.
New Window into Planet Formation with Webb’s MIRI

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With its exquisite sensitivity, high angular resolution, and moderate spectral resolution, the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope will open new windows into many facets of the universe, including the processes by which planetary systems form and evolve. To advance this area of science, MIRI will make unique observations of two types of circumstellar disks—protoplanetary disks around young stars, where planets maybe forming, and debris disks around more mature stars, where the debris is produced by the collisions between small planetary bodies. For example, MIRI will constrain the location and abundance of water in protoplanetary disks, and will spatially resolve thermal emission from dust in debris disks—in both cases around stars with a wide range of masses, from brown dwarfs to solar-mass stars.

Volatile molecules—e.g., H₂O, CO₂, CH₄, and HCN—play a central role in the formation of planetary systems. This is reflected in the structure and composition of the Solar System, and theory predicts that volatiles are equally important for the formation of exoplanetary systems. Out beyond the snow line—the minimum distance from a star at which water condenses, typically 1–5 AU—volatiles dominate the solid mass in protoplanetary disks, and therefore drive the formation of planetesimals (e.g., Johansen et al. 2009) and planets that are formed through core accretion processes (Dodson-Robinson et al. 2009). Also, the evolution of volatiles dictates the availability of ingredients for life—on the Earth, as well as on terrestrial planets and moon systems around other stars (Raymond et al. 2004).

MIRI will permit detailed studies of bulk volatiles (species that dominate the condensable mass) near snow lines in the era when planetesimals form in gas-rich protoplanetary disks. This research will be accomplished by mid-infrared spectroscopy of the molecular “emission forest” that characterizes typical planet-forming disks around young (~1–5 Myr) stars. Recent Herschel observations find far-infrared lines are generally absent or weak, demonstrating extremely low abundances of water beyond a few AU in typical disks (e.g., Hogerheijde et al. 2011). Combining the Herschel results with mid-infrared observations of the molecular forest can measure the location of the snow line (Zhang et al. 2013).

As illustrated in Figure 1, the InfraRed Spectrograph (IRS) on Spitzer acted as a critical trailblazer for MIRI. Spitzer made the first mid-infrared detections of the molecular forest in protoplanetary disks, and developed the demographics of molecular gas in planet-forming regions (prevalence and chemistry, as well as dependencies on the stellar mass and evolutionary stage) (Carr & Najita 2008; Salyk et al. 2008; Pontoppidan et al. 2010; Carr et al. 2011). These initial Spitzer results have raised a long list of questions that can only be answered by Webb. For instance, the physical parameters of disk molecules—e.g., abundance, temperature, and distribution—are uncertain due to the IRS’s relatively low spectral resolving power (Salyk et al. 2011). At R ~ 600, molecular lines are highly blended, making it very difficult to measure individual lines. For water, this defect is critical since the blends typically include and combine transitions from widely separated energy levels. The higher resolving power of MIRI (R ~ 3000) permits the separation of most water lines, and will enable detailed measurements of molecular abundance and spatial distribution (Pontoppidan et al. 2009).

Further, Spitzer was sensitivity-limited to disks around stars more massive than ~0.5 M☉. Conversely, MIRI can observe molecular emission from disks spanning the entire stellar and substellar mass range within several kpc. Further, while Spitzer observed essentially all of the ~100 disks that were bright enough for this type of study, MIRI will be able to select from a diverse potential sample of up to 100,000 protoplanetary disks. This permits a careful construction of robust, unbiased statistical
studies, which may turn out to be critical, as the total number of targets that can be observed one-by-one with Webb in a reasonable time is limited.

Finally, Spitzer did not detect water in disks around early-type stars (spectral types F–B). One possible explanation is that the bright continuum of these disks masked the very under-resolved lines in the Spitzer spectra, making the line-to-continuum ratio too small for detection. Simulations show that the higher spectral resolution of MIRI may reveal water emission around these objects by increasing the dynamic range of line sensitivity above the bright disk continuum by at least an order of magnitude.

Debris disks
Debris disks are dusty disks around main-sequence stars. In these exoplanetary systems, the dynamics of the planets, small bodies, and dust grains are determined by stellar and planetary properties alone (e.g., stellar luminosity, stellar mass loss, and gravitational attraction). As illustrated in Figure 2, structural features have been found in debris disks that may be due to unseen planets. In this theory, the debris comes from colliding minor bodies—e.g., asteroids or comets—that have been perturbed into crossing orbits by the planets. In fact, the giant planets around β Pictoris and Fomalhaut were inferred to exist from observations of non-axisymmetric disk structure (Heap et al. 2000, Kalas et al. 2005) before they were discovered in high contrast-imaging studies as illustrated in Figure 3.

Debris disks can be used to investigate three important phases of the formation and evolution of planetary systems: (1) the middle-to-late stages of terrestrial planet formation, which included the Moon-forming event in our Solar System; (2) Jovian-planet migration, which included the Jupiter and Saturn crossing of the 2:1 resonance, which may have triggered the late heavy bombardment of the terrestrial planets (Morbidelli et al. 2012); and (3) the final, end-state architecture of planetary systems.

The IRS and the Multiband Imaging Photometer on Spitzer measured a wealth of debris disk spectral energy distributions (SEDs) for the first time (e.g., Rieke et al. 2005, Carpenter et al. 2009). SEDs indicate that debris disks generally possess large central clearings, consistent with the presence of planetary companions (Chen et al. 2006). However, SED models are degenerate with respect to the grain properties—e.g., size, composition, and shape—which are currently not well understood. Recent Herschel observations marginally resolve cold Kuiper Belt analogs in the nearest debris disks and suggest that SED-inferred dust distances are accurate to a factor of two. MIRI is expected to dramatically increase the number of Kuiper Belt analogs that are spatially resolved, measuring the sizes of hundreds of nearby debris disks (Smith & Wyatt 2010). In addition, MIRI is also expected to characterize warm dust in asteroid belt analogs, marginally resolving these objects around the nearest intermediate-mass stars.

MIRI possesses four coronagraphs, three four-quadrant phase masks, which operate at 10.65, 11.4, and 15.5 µm, and one Lyot coronagraph that operates at 23 µm. These are expected to suppress light from the central star by a factor of ~100–400 without subtracting the point-spread function, and to allow studying disk structures in greater detail.

Current models for Vega hypothesize that this system possesses a 30 $M_{\text{Earth}}$ planet, which may have migrated from 45 AU to 60 AU (Wyatt et al. 2003). Such a planet is expected to (1) gravitationally scatter out of the system dust grains that are migrating inward under Pointing-Robertson drag, and (2) trap large grains into resonant structures. Collisions between parent bodies within resonant structures are expected to generate small grains, which would be sensitive to radiation pressure and blown into spiral structures (Wyatt et al. 2006, Muller et al. 2010). As illustrated in Figure 4, MIRI is expected to spatially resolve the central clearing of the Vega disk and allow a search for asymmetric structures due to planets.
When combined with scattered-light and submillimeter maps of thermal emission, MIRI maps of mid-infrared thermal emission are expected to further enrich our understanding of young planetary systems. By comparing the disk surface brightness in scattered light with that in thermal emission, observers can measure the albedo of the disk, which constrains the composition of the dust. The majority of debris disks are believed to be analogs of the Kuiper Belt, which is populated by icy dust. Submillimeter thermal emission maps are sensitive to larger grains trapped in resonances with planets. Maps of mid-infrared emission are sensitive both to smaller grains that are radiatively driven from the system and moderate-sized grains that are too small to be trapped into resonances and too large to be sensitive to radiation pressure.

In conclusion, MIRI is expected to enhance our understanding of the formation and evolution of planetary systems by characterizing (1) the reservoir of volatiles available for the formation of terrestrial planets and (2) the location and composition of minor bodies during the end game of planetary system evolution.

References


Figure 4: Simulated Webb MIRI 23-micron Lyot coronagraphic images of Vega before (left) and after (right) subtracting the point-spread function. Models assume either moderate-sized grains that are insensitive to radiation pressure (top) or a mixture of small, radiation-pressure sensitive grains and moderate-sized grains (bottom). Credit: Christine Chen, Rémi Soummer, and Mark Wyatt, STScI.
New MESA Group Has a Systems Perspective

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The Instruments Division is home to most of the instrument scientists and analysts at the Institute. Until last year, division support for the James Webb Space Telescope was drawn mainly from the Webb Instrument Team (WIT), with the remainder coming from the Telescopes group. As Institute preparations for Webb ramped up, the size of the WIT grew to more than 30 people. In response, the WIT split in May 2012 into separate groups for the four Webb instruments: Near Infrared Camera (NIRCam), Near-Infrared Spectrograph (NIRSpec), Near Infrared Imager and Slitless Spectrograph (NIRISS), and Mid Infrared Instrument (MIRI). Support for the Webb Fine Guidance Sensor (FGS) moved to the Telescopes group. We also created the Mission Engineering and Science Analysis (MESA) group to coordinate work across instruments—and even across missions. We continue to use “WIT” as an informal term for all Webb support in the Instruments Division, even though, formally, that support is now spread across six groups.

The philosophy of MESA

A guiding principle of Webb support at the Institute is that coordinated approaches across instruments are often better than separate but equivalent approaches. The instruments have different capabilities, but from a science and operations perspective they share many requirements. MESA identifies shared requirements and convenes cross-instrument working groups to find common solutions. For example, Webb instruments measure charge as it accumulates in detector pixels during an exposure, and we need to convert charge ramps into count rates for all instruments. This conversion requires algorithms to handle reference pixels, nonlinearity, cosmic rays, pixel crosstalk, and more. Therefore, MESA supports cross-instrument working groups to define which of the many possible algorithms are actually implemented in the Webb calibration pipeline. In this way, defining common algorithms and common terminology avoids redundant development efforts and simplifies learning about multiple instruments by comparison and contrast.

Cross-instrument working groups

Currently, MESA supports the following cross-instrument working groups for Webb:

- Exposure time calculators
- Proposal and planning system
- Operations
- Observatory efficiency
- Calibration and commissioning
- Pipeline
- Archiving ground-test data

This working group sequence reflects the progressive stages of an observing program: conception, implementation, execution, calibration, and archiving. Each working group has at least one representative from each Webb instrument group at the Institute. Meanwhile, external instrument teams participate in the operations and calibration working groups. Institute engineers interact frequently with the working groups, as we jointly define the capabilities of our ground system to operate Webb. Individuals from Webb instrument groups or MESA personnel lead the working groups, MESA supports the working groups by developing processes, coordinating activities, and recording results.

Operations Detector Lab

MESA is also the home of the Operations Detector Lab (ODL) at the Institute. ODL maintains a lab with a dewar for cryogenic experiments, a flight-like near-IR detector system, and, for independent testing, a controller commonly used in ground-based observatories. ODL performs detector experiments that inform operational procedures and data analysis algorithms. For example, ODL is currently investigating a practical method to characterize persistence in every pixel, at all well depths. This persistence model may become the basis for a correction in the calibration pipeline. ODL also analyzes data obtained elsewhere during ground tests. For example, ODL is currently analyzing MIRI ground-test data in order to develop an algorithm for removing low-level, periodic perturbations in the bias level.
Cross-mission synergy

Formed in the WIT restructuring, MESA initially had a strong Webb focus. However, MESA aspires to find cross-mission opportunities to pursue synergistic developments. A good example—predating MESA—is the development of a new calibration system for reference data, which both Hubble and Webb will use. Hubble systems occasionally require refreshing as technology advances. At the same time, Hubble can take advantage of developments needed for Webb. And Webb benefits by having its newly developed systems tested in the Hubble operational environment. As one example, MESA has begun investigating data-processing tools that Webb needs, but also might benefit Hubble.

The future

MESA is approaching the anniversary of a successful first year. The use of cross-instrument working groups is functioning smoothly now for Webb. We are planning to strengthen interactions between these working groups and the numerous engineering groups at the Institute. In the coming year, MESA will strive to incorporate Hubble into the cross-instrument working groups and the cross-mission efforts.

Webb and the Solar System

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The James Webb Space Telescope will peer into the depths of space and back in time to reveal the earliest epochs of our universe. But it also will look at our cosmic backyard, the Solar System, for clues to how planets form and evolve with time. Webb’s unprecedented combination of sensitivity, spatial resolution, and spectral range give it a unique set of capabilities for observing a wide variety of objects in the Solar System. With the implementation of moving-target tracking on the facility, detailed planning has begun. To that end, workshops on Webb Solar System observations were held at the 2008 and 2012 annual meetings of the Division for Planetary Sciences of the American Astronomical Society. At these workshops, planetary astronomers discussed the science potential and the challenges of observing the Solar System with Webb. This short report highlights a few of the types of observations that can be done with the facility and some challenges that must be addressed.

Kuiper Belt

In the Solar System beyond Neptune lies the Kuiper Belt, a dynamic, rag-tag collection of objects (called KBOs) left over from the formation of the Solar System. They range downward in size from the so-called dwarf planets Pluto and Eris—each about 2300 km across. KBOs have a wide range of colors, from gray to extremely red. Observations in the optical and thermal infrared, which can untangle the size and reflectivity of the brightest KBOs, indicate a broad range of visible-wavelength reflectivities, from coal black to almost perfectly reflecting. Spectroscopic studies from ground-based telescopes of the largest KBOs reveal variable compositions, with water ice, methane, nitrogen, and carbon monoxide on Pluto, but only methane detected on Eris. Most KBOs are simply too small, distant, or dark for ground-based spectroscopy to yield much information, and the wavelength range of such studies is limited to parts of the near-infrared.

With its wavelength range of 0.6–29 microns, and its ability to perform high-resolution spectroscopy (λ/Δλ = 3000), Webb will constrain isotopic ratios in the water ice and other components on Pluto and Eris, as well as provide surface-temperature monitoring through the nitrogen overtone band. Detection of non-water ices on surfaces of smaller or more distant KBOs, including the enigmatic Sedna, will be possible with Webb. In total, Webb will perform on Kuiper Belt bodies, which have varied and complex surfaces (see Figure 1), the same range of compositional studies done now in the much closer, main asteroid belt.

Figure 1: Voyager 2 image of Neptune’s moon Triton, thought to be a captured Kuiper Belt object, showing the complexity of its surface. A nitrogen polar cap, ringed by methane deposits, lies atop water ice. Credit: NASA/JPL.
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Titan

The second-largest moon in the Solar System after Jupiter’s Ganymede, Saturn’s Titan has a dense and cold—94 K at the surface—nitrogen atmosphere with 1–5% methane, and a variegated surface of water ice, which is overlain by organics in solid and liquid form. Though only weakly heated by the Sun, Titan has a climate system that exhibits cloud formation, methane rain, and rivers, lakes, and seas of methane—as well as the stratospheric chemical product of methane, ethane. In some respects, the cycle of methane from surface-to-lower atmosphere mimics the hydrologic cycle on Earth, only the 29.5-year orbit of Saturn around the Sun means that the seasons on Titan—which has a tilt just a few degrees more than Earth’s—last seven years. The Cassini mission has observed seasonal changes on Titan over the past eight years, and will continue to do so until mission’s end in 2017, when about half a Titan year will have transpired. With its clouds and hazes at various altitudes, the complex nature of Titan’s atmosphere taxes the capabilities of optical, near-infrared, and mid-infrared instruments on Cassini.

Webb will take over from Cassini in 2018, observing the changing face of Titan over a similar broad wavelength range, up through northern-fall equinox. Through the combined efforts of Cassini and Webb, observations covering from the surface of Titan to its upper atmosphere over nearly two-thirds of its year will have been completed. During the 2009 spring equinox, large outbursts of equatorial clouds were observed, along with surface darkening, which has been interpreted as methane wetting the water ice (see Figure 2). The potential for observing similar behavior during the fall equinox in 2023—still within Webb’s prime mission—makes it imperative to have high sensitivity, spectral range, and resolution available to observe Titan.

![Figure 2](image-url)

Figure 2: A cloud outburst observed from NASA’s IRTF telescope in 2008 demonstrates that observations from 1 AU are capable of discerning atmospheric phenomena on Titan. Figure from Schaller, E., et al. 2009, Nature, 460, 873–875; copyright Nature publishing.
Giant planets

The giant planets of the Solar System represent both a promise and a challenge for Webb. A variety of atmospheric features can be observed with high sensitivity over a broad range of wavelengths. Nevertheless, in some cases the high brightness of these objects requires very short exposures with Webb. These can be executed in special observing modes called subarrays, where only a small subset of the detectors full pixel array is used for the observation and is recorded much faster. The ability to observe over Webb’s large wavelength range opens the possibility for unprecedented, simultaneous studies of atmospheric phenomena over a broad range of altitudes, as well as studies of auroral emission in H-filter and of trace species, such as CO in fluorescence.

Webb’s spectra of the Solar System’s giant planets will provide “ground truth” for interpreting its spectra of exoplanets, and thus tie together the observations by this remarkable observatory of our planetary system and others.

Conclusion

The observations sketched in this article represent only a subset of those that Webb will be able to make of our Solar System.

In addition to the brightness of Solar System objects, a number of other challenges in making Solar System observations were identified by participants in the 2012 workshop, including the details of scheduling moving-target observations and of accounting for the time costs of slewing the telescope. Nevertheless, such challenges are typical for a complex observatory, and will be surmounted. Once launched, Webb will provide us with views of the Solar System unique in their sensitivity and spectral range.

General sources


A New Frontier: Observations of Exoplanet Atmospheres with the James Webb Space Telescope

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The future of exoplanet atmospheric studies resides in the James Webb Space Telescope. With its large aperture and infrared spectroscopic capability, Webb will open opportunities to study planets as small as terrestrial size, taking us far beyond current studies of exoplanet atmospheres, which are limited mostly to hot Jupiters. Webb will access a wide variety of exoplanets, falling into two categories. First are the self-luminous young planets (down to about Saturn’s mass) with wide orbital separations, i.e., with apparent separations greater than a few arcseconds, so the images of the star and planet are distinct (e.g., Beichman et al. 2010). Second are the transiting planets of all sizes, where adequate angular separation is not an issue, but the required orbital alignment will be fortuitous and infrequent, limiting the numbers of transiting planets accessible for study.

Here we focus on the transiting mini Neptunes and super Earths, which are enigmatic planets with no solar system counterparts. The so-called mini Neptunes—planets of about 2 to 3 Earth radii (or about 10 to 30 Earth masses), which by their sizes and/or densities must have hydrogen or hydrogen-helium gas envelopes—are extremely common, as found by Kepler (Figure 1; Fressin et al. 2013), by radial velocity observations (Howard et al. 2010), and by microlensing surveys (Cassan et al. 2012). Mini Neptunes are
likely to be ten times more common than Jupiter-size or Jupiter-mass planets. Nevertheless, we do not have a good understanding of the origin or composition of the mini Neptunes. Super Earths—planets that are predominantly rocky with thin atmospheres—are so interesting because those with cool enough surface temperatures may be suitable for life.

Webb will be an exoplanet-characterization machine, following up known transiting exoplanets, one planet at a time.

The opportunity for Webb to study the atmospheres of small planets is centered on M dwarf stars hosting transiting planets. To understand why, we only need to consider a key concept, which is that the atmosphere is observed in the combined light of the planet-star system. Indeed, it is the on/off nature of the transit or secondary eclipse that enables the planetary transmission or emission spectrum to be extracted (Figure 2). Therefore, the smaller the star, the more favorable is the planet-star contrast. The characteristic magnitude of the transmission-spectrum signal (observed when the planet is in front of the star) can be estimated as the ratio of the area of the annulus of the planet atmosphere (about $10\pi R_{\text{planet}}^5$ for five scale heights $H$) to the star area $\pi R_{\text{star}}^2$. The scale height is defined by $H = kT/\mu_m m_H g$, where $k$ is Boltzmann’s constant, $T$ is temperature, $\mu_m$ is the mean molecular weight, $m_H$ is the mass of the hydrogen atom, and $g$ is the surface gravity.

Strong molecular bands can be optically thick in transmission over many scale heights, so atmospheres that stretch this absorption over the maximum height range (that is, have large scale-heights) block the most star light and produce maximum absorption in transmission spectra. The scale-height dependence explains why observations of transmission spectra favor hot or hydrogen-rich atmospheres on planets with low surface gravities and not, in contrast, planets with high bulk density and thin atmospheres of high molecular weight.

Because most molecules are spectroscopically active at near-infrared (NIR) wavelengths, and because M-star fluxes peak in the NIR, all three Webb NIR instruments—Near-Infrared Spectrograph (NIRSpec), Near-Infrared Camera (NIRCam), and Near-Infrared Imager and Slitless Spectrograph (NIRISS)—are suitable for transmission spectroscopy or spectrophotometry.

Turning to thermal-emission measurements via secondary-eclipse observations, the planetary temperature is key. Here, the characteristic signal can be estimated by the ratio $T_{\text{planet}} R_{\text{planet}}^2 / T_{\text{star}} R_{\text{star}}^2$. Webb’s Mid-
Infrared Instrument (MIRI) is well-suited to observe atmospheric absorption bands in cooler planets, with the thermal emission of habitable-zone planets peaking in the mid-infrared. We expect transit or eclipse signals to range from tens of parts per million for CO2 atmospheres on habitable-temperature planets to nearly a part per thousand for hot mini Neptunes.

Characterizing the atmospheres of small exoplanets is a program ripe for fundamental discoveries. The first question for the mini Neptunes is: what are they made of? We hope that, in some cases, atmospheric observations can reveal interior composition. For example, a saturated, thick, hot, water-vapor atmosphere for a small enough planet could indicate a “water world”—a planet akin to a scaled-up version of Jupiter’s icy moons. For super Earths, we simply want to know if any planets have thin, terrestrial-like atmospheres, dominated by CO2 spectral features.

Beyond the quest to understand the atmospheric compositions of super Earths and mini Neptunes, Webb will provide other exciting firsts, such as the 3D “mapping” of the atmospheres of exoplanets of mini-Neptune-to-Jupiter size: 2D surface hot spots and other features can be mapped using transit and eclipse ingress and egress, together with phase curves; the additional dimension is atmospheric altitude, probed by measurements at different wavelengths that may correspond to different optical depths, and hence, altitudes (e.g., de Wit et al. 2012). Across the board, detailed simulations of what is possible with potential Webb observations of exoplanets are growing in the literature (e.g., Deming et al. 2009; Kaltenegger & Traub 2009; Belu et al. 2011; Benneke & Seager 2012).

To detect molecular signatures in the small-exoplanet atmospheres, a large allocation of telescope time per planet will be needed. Given that transits last from a few to several hours, and that tens of transits must be binned together to reach a significant detection, time allocations on the scale of a Hubble Deep Field may be required per planet. Also, very careful scheduling of observations will be needed. Some planets of interest will transit their stars every 30 days or longer. It is conceivable that Webb will be tasked to observe all technically feasible transits and eclipses that occur during its five-year mission.

Figure 3: Webb/NIRSPEC simulated exoplanet transmission spectra from Deming et al. 2009. The red or blue lines are the modeled spectra. The synthetic data, shown in black, have been smoothed in wavelength, by binning, from an original spectral resolving power of R = 1000, down to R = 100. Each panel shows a planet with different physical characteristics. The figures on the left show water absorption, and those on the right show CO2 absorption. Upper left: water absorption near 2 μm for a hot (T = 506 K) super Earth of radius 2.1 times Earth, at a distance of 32 pc. In this example, the signal-to-noise ratio (S/N) for the aggregate detection of water absorption is S/N = 163 for 301 hours of observing. Bottom left: again water absorption near 2 μm but for a habitable super Earth having T = 302 K and radius 1.8 times Earth, at 20 pc; S/N = 16 for 122 hours. Top right: CO2 absorption near 4.3 μm for a hot (T = 797 K) super Earth of radius 2.2 times Earth, at 18 pc; S/N = 150 in 480 hours. (The S/N for 20 hours would scale down to 31.) Lower right: CO2 absorption in a habitable super Earth having T = 308 K and 2.3 Earth radius, at 22 pc; S/N = 28 in 85 hours. For more details see Deming et al. 2009.
Systematic effects in Webb instruments pose further challenges to exoplanet observations. Pointing jitter of the stellar image with respect to the detector pixels is expected to be the largest source of systematic noise, as we have learned from Hubble, Spitzer, and Kepler observations. In general, minute changes in detector response across and between pixels cause wavelength-dependent intensity oscillations in aperture photometry. Although it is now standard observing practice to try to keep the target-star image on the same pixel subsets at all times, even small pointing drifts or anomalies, or thermal cycling effects on the detector, can induce intensity changes larger than the sought-after signal of the exoplanet atmosphere. Fortunately, a method to measure the variation of the intrapixel sensitivity for the Fine Guidance Sensor (FGS) has been developed, and because the FGS’s HgCdTe detectors are the same as those used in NIRCam and NIRSpec, a calibration to mitigate the problem may be available. More importantly, it may be possible to measure intrapixel sensitivity during Webb operations, using a new “fine pointing” capability via the steering mirror rather than motion of the entire spacecraft (Clampin et al. 2013, in prep.).

For MIRI, we expect additional systematic effects due to background thermal emission from the instrument, telescope, and sun shade. For all Webb instruments, we expect as-yet-unknown temporal systematics that will differ from transit to transit, which will have to be identified and carefully removed from the data. The ultimate goal in studying exoplanet atmospheres is the search for signs of life via biosignature gases—gases generated as metabolic byproducts, which can accumulate to detectable levels. Is there any hope that the Webb could be the first to provide evidence of biosignature gases? Yes, if—and only if—every single factor is in our favor. First, we need to discover a life-bearing super Earth (preferably with an atmosphere rich in molecular hydrogen), orbiting a very nearby, quiet M star. Second, the life must thrive and produce biosignature gases that are spectroscopically active (see Seager et al. 2013). Regardless of the search for life, Webb is poised to open a new era in exoplanet characterization by bringing studies of exoplanet atmospheres to a completely new level.

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References


The *Webb* education and public outreach program is a collaboration of the Institute, NASA, ESA, CSA, Northrop Grumman, and other partners. Over the last few years, the broader outreach team has increased efforts to inform educators and the public about *Webb*, mostly adapting the proven infrastructure developed for the *Hubble Space Telescope*. These efforts have included developing a website (www.webbtelescope.org), designing and disseminating multimedia and print products, building an audience via social media, and initiating the *Webb* STEM Innovation Project (https://blogs.stsci.edu/newsletter/2012/12/19/bringing-the-webb-mission-to-the-education-community/). The goal of these activities is to tell the world about *Webb*’s potential to address the most profound questions we have about the universe.

In the spring of 2012, in a unique cultural context, the team launched a new project for a segment of the public not previously targeted. Our idea was to bring *Webb*—literally—to where tens of thousands of people would gather: South by Southwest (SXSW), which is an annual festival in Austin, Texas. The interactive portion of SXSW is a proven technology magnet, bringing together leaders in innovation from around the world. The proposal to SXSW Interactive was a collaboration of our *Webb* outreach partners, the astronomy department of the University of Texas (UT) at Austin, and Microsoft Research’s WorldWide Telescope (WWT; http://www.worldwidetelescope.org).

The proposal described over a dozen activities, each highlighting an aspect of *Webb*’s science, engineering, and technology facets and involving direct engagement with students and adults. The organizers of SXSW Interactive selected the proposal as the centerpiece for the Science and Space Exploration theme of the festival, and the event took place on March 8–10, 2013.

**The full-scale model of *Webb***

The primary feature of the outreach event at SXSW was Northrop Grumman’s full-scale model of *Webb*. The model was installed on the lawn of the Long Center for the Performing Arts, near the site of the SXSW Gaming Expo, just a short walk away from Austin’s busy downtown. The sheer size of the *Webb* model, 22 × 12 meters, along with its unconventional shape, drew attention and sparked
curiosity from passersby. The results were amazing: over the course of three days, more than 15,000 people came by to examine Webb more closely.

With help from UT astronomers, we trained a team of over 20 graduate students to explain Webb’s design and science goals to the public. While walking visitors around the model, our staff explained the five-layer, tennis-court-sized sunshield, which cools the telescope mirrors and instruments. They explained other unique features of Webb, such as the segmented, 6.5 meter primary mirror, and the deployable nature of the entire observatory. These discussions naturally inspired all manner of follow-up questions, for example about the planned orbit of the telescope, the reason for mirrors coated with gold, and the differences between Webb and Hubble. After a tour of the full-scale model, people flowed on to the “Webb Experience” pathway, with large illustrations of the science and technology behind Webb, and moved towards the “NASA Experience” tent.

The NASA Experience tent

The purpose of the NASA Experience tent, which measured 33 × 12 meters, was to give the public an interactive, hands-on experience learning about Webb. Inside the tent, people were able to actually touch real Webb test hardware, such as backplane structures and Kapton sunshield material. They could stand in front of a full-size mirror segment. Our team set up an infrared camera to demonstrate heat radiation. UT students exhibited their own Webb-related STEM projects, pursued under our formal education programs. The NASA Experience tent was packed with hundreds of people at all times during the three-day event.

The Microsoft Visualization Wall

The partnership with Microsoft Research and WWT helped to communicate the science and engineering behind Webb. WWT set up a six-meter Visualization Wall at the back end of the NASA Experience tent. This amazing screen presented 15-minute presentations by dozens of scientists and engineers. It also facilitated custom-built WWT tours and Skype chats with engineers in the clean room at Goddard Space Flight Center where real Webb hardware is being tested. In all, more than 60 presentations were delivered on the Visualization Wall—one every 30 minutes—mostly to packed audiences of 150–250 people.

The WWT tours effectively communicated the scale of the universe and the diversity of the Webb science case. The tours panned through our Solar System, circled around our Galaxy, and zoomed into the deepest images in astronomy, like the Hubble Ultra Deep Field.

Among the most popular lectures were keynotes by Nobel laureate Dr. John Mather and Institute director Dr. Matt Mountain.

In addition to the Visualization Wall, Microsoft installed two 82” touch-screen monitors, which gave the public a way to explore the universe at their own pace. The monitors were pre-loaded with a custom-built Windows 8 application that accessed information on the science, engineering, and innovations of Webb and Hubble. The monitors also connected to WWT. The area around the monitors became gathering points for many impromptu lectures by team astronomers and engineers.

The Webb mirror exhibit

Adjacent to the Webb full-scale model, we installed a new exhibit allowing the public to understand the size of the primary mirror. This exhibit shows several of the Webb mirror segments at their true size, and includes a spot where one can view, through a reflection, the full size of the array of 18 mirror segments. The mirror exhibit was a hit. Thousands of people came by and took turns standing on the spot. Team members took the opportunity to explain that a large mirror is crucial to answering the big science questions in astronomy.

Social media and the “Beyond Hubble” science panel

On the morning of March 10, NASA organized an event to bring more than a dozen followers of NASA social media to our exhibits in the NASA Experience tent. Four of our staff members—John Mather, Scott Willoughby, Jason Kalirai, and Amber Straughn—gave presentations and answered questions. Because the followers themselves have large followings, this event had a large multiplier effect for our
communication goals at SXSW. Many participants in the social-media event also attended a science panel we organized in downtown Austin. The panel, titled “Beyond Hubble: The James Webb Space Telescope,” featured presentations on Webb by Matt Mountain, Alberto Conti, and Blake Bullock, as well as one presentation on WWT by Jonathan Fay. The panel was well attended and a success, at least as judged by one attendee who was heard to comment, “That was pretty much awesome! My mind is completely blown.”

A new Guinness world record

On the evening of Sunday, March 10, the Webb education and outreach team broke a Guinness world record for the largest astronomy lesson. This event was advertised throughout the festival, and 526 people—the official number!—showed up next to the full-scale model to hear about light and spectroscopy. (The actual number was larger, but Guinness rules required that the area used for the record attempt be closed at 7:30 p.m. sharp.) Jason Kalirai and Amber Straughn warmed up the audience with an impromptu talk and Webb trivia quiz. The Institute’s Frank Summers and Dan McAllister delivered the formal lecture to the record-breaking audience.

Impact

Through SXSW, our team communicated Webb science, technology, and engineering directly to more than 15,000 people. We reached further millions over social media. Late on the last evening, during the Guinness record attempt, “#JWST” on twitter was trending in the Texas area. Over the course of the three days, the discussion of Webb on twitter increased by 1500%, and the number of followers of our accounts increased by 400% over expectations in the absence of SXSW. Other social media accounts, such as Facebook, saw similar gains. More than 40 news and media outlets reported about the Webb events at SXSW, including the Los Angeles Times, the Washington Post, Scientific American, and some of the biggest online news sites, like Mashable.

Aside from such metrics, the astronomers and engineers who supported the Webb event at SXSW felt they made a big, even if unmeasured, impact on the young students they engaged and attempted to inspire over the three-day event.
The Barbara A. Mikulski Archive for Space Telescopes (MAST) is NASA’s data repository for astronomy missions at ultraviolet, optical, and infrared wavelengths. These include Hubble, GALEX, Kepler, XMM-OM and Swift-UVOT, future missions such as Webb, past missions (FUSE, IUE, EUVE, and others), and all-sky surveys such as VLA-FIRST, GSC and DSS.

MAST supports the scientific research carried out by the astronomical community by facilitating access to its collections, offering expert user support and software for calibration and analysis, and providing value-added scientific data products. These include high-level science products (HLSPs) such as mosaics, catalogs, and spectra delivered to MAST by science teams, as well as enhanced products accessible via the Hubble Legacy Archive (HLA).

As of March 2013, the total volume of MAST’s data holdings was approximately 231 terabytes (TB), with an average of 18 million searches per month and 16 TB of data downloaded per month.

Social media
MAST has added a variety of social-media features on our webpages to facilitate engagement with our community. Be sure to “like us on Facebook” (https://www.facebook.com/MASTArchive) and “follow us on Twitter” (https://twitter.com/MAST_News). Be the first to know when new data and analysis tools become available in our archive for your use. Learn about resources on our sites you may not know about, which might improve your research efficiency and increase your potential for discovery. Finally, feel free to contact us via Facebook and Twitter to pose questions, or send comments and suggestions about our site. You can even see our recent updates and tweet us through our own webpage (http://archive.stsci.edu/followus.html).

High-Level Science Products: Multi-Cycle Treasury Programs
All three Multi-Cycle Treasury (MCT) programs are in their final cycle and have recently released a variety of new, high-level science products, bringing the total to almost 3 TB of mosaics and other products delivered to the archive by these teams. These can be accessed from the main HLSP page at http://archive.stsci.edu/hlsp/ and each of these three programs are summarized here:

The Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; PI: S. Faber and H. Ferguson; http://archive.stsci.edu/prepds/candels) has recently released the final, v1.0, full-depth, combined mosaics for the GOODS-S and COSMOS fields. Along with the UKIDSS/UDS field, complete CANDELS mosaics for a total of three fields have now been fully released and delivered by the team. Observations are still ongoing for the remaining two fields, EGS and GOODS-N; the most recent deliveries of high-level science products for these fields include v0.5 drizzled mosaics for epoch 7 of GOODS-N. The CANDELS survey has yielded science results on galaxy evolution up to redshift \( z = 8 \), morphologies of galaxies at \( z = 2 \), the properties of high-redshift supernovae, and the evolution of active galaxies. The project has delivered high-level v0.5 and v1.0 mosaics and other science products for 748 orbits out of the total of 902 orbits. To date, a total of 30.8 TB of the CANDELS survey’s high-level products and mosaics have been downloaded by the community to 1030 distinct IP addresses.

The Cluster Lensing and Supernova Survey with Hubble (CLASH; PI: M. Postman; http://archive.stsci.edu/prepds/clash) has released data products for three new clusters: Abell 209, MACS0416, and RXJ2248. This project has now released high-level mosaics and catalogs for a total of 20 clusters, each of which has been observed with up to 16 Hubble filters, including four ultraviolet filters in the ultraviolet-visible channel Wide Field Camera 3 (WFC3/UVIS), seven optical filters in Advanced Camera for Surveys (ACS), and five filters in the infrared channel of WFC3 (WFC3/IR). Science results from the...
Figure 1: The most recent v1.0 deliveries by the CANDELS team, consisting of full, combined mosaics of the CANDELS GOODS-S field. These mosaics are the full combination of 15 epochs of observations with ACS (left) and WFC3/IR (right) in seven filters, and are constructed from 230 orbits obtained between 2010 and 2012. They achieve limiting magnitude depths of 28–28.5 AB (5 sigma) in all the filters.

Figure 2: CLASH mosaics of the three most recently released clusters, Abell 209 (left), MACS0416 (middle) and RXJ2248 (right), constructed from the full 16-filter Hubble datasets.

Figure 3: Several examples of multi-filter PHAT tiles for a subsection of one of the most recently delivered datasets (“brick 08,” location “f17,” delivered January 2013), showing WFC3/UVIS (left), ACS/WFC (middle), and WFC3/IR (right) of the same area on the sky. This highlights the range of different stellar populations probed by the wide range of filters used in this survey.
survey include objects at $z = 9–10$, lensed galaxies at $z = 6$, and results on cluster properties. To date, a total of 1.1 TB of CLASH mosaics have been downloaded to 900 distinct IP addresses.

The Panchromatic Hubble Andromeda Treasury Program (PHAT; PI: J. Dalcanton, http://archive.stsci.edu/prepds/phat) has released new combined mosaics and catalogs for the “bricks” that are being used to tile the Andromeda galaxy, with a total of 14 bricks having been delivered to date. The remainder of the 23-brick total is currently being observed. The mosaics for each brick consist of six filters in WFC3/UVIS, ACS and WFC3/IR, obtained in a $3 \times 6$ array of pointings. This survey has yielded science results on the dynamics and structure of M31, and on the properties of its stellar populations. A total of 4.7 TB of PHAT mosaics and other products have been downloaded to date, to 428 distinct IP addresses.

Other recent releases of High-Level Science Products

The Hubble Ultra Deep Field 2012 (HUDF12; PI: R. Ellis; http://archive.stsci.edu/prepds/hudf12) released the full-depth v1.0 mosaics of the UDF, incorporating all WFC3/IR data previously obtained (including data from the HUDF09, PI: G. Illingworth, as well as CANDELS and other projects). The final combined mosaics are constructed from a total of 253 orbits, including 100 orbits in F105W, 39 orbits in F125W, 30 orbits in F140W, and 84 orbits in F160W, and reaching limiting AB magnitudes of $29.5–30$ (point source, 5 sigma sensitivities).

Figure 4: The full-depth HUDF12 mosaic dataset, consisting of 253 orbits in F105W, F125W, F140W and F160W, and reaching limiting AB magnitudes of 29.5–30.0 (5 sigma) in these filters.

The Orion Nebula HST Treasury Program (PI: M. Robberto, http://archive.stsci.edu/prepds/orion) has delivered catalogs and images from ACS, Wide Field Planetary Camera 2 (WFPC2), and Near Infrared Camera and Multi-Object Spectrometer (NICMOS). This program is aimed at obtaining deep, multi-color photometry of thousands of sources with masses well down into the brown-dwarf regime, complemented by a rich set of ancillary data from ground-based observatories.
Hubble Legacy Archive

Data Release 7 of the HLA is now available. The new data products contained in this release include 586 spectra from the StarCAT project (http://archive.stsci.edu/prepds/starcat/), new mosaics and related data products released by the CANDELS, CLASH and PHAT MCT programs, and new imaging products from the BORG (Brightest of Reionizing Galaxies; http://archive.stsci.edu/prepds/borg/), Orion and GHOSTS (Galaxy Halos, Outer disks, Substructure, Thick disks and Star clusters; https://archive.stsci.edu/prepds/ghosts/) surveys. This release also contains a number of significant user interface enhancements, including:

• scatter plotting tool that allows users to plot the properties of the HLA source lists
• the ability to view spectral HLSPs through the interactive display
• faster overlay of catalogs in interactive display
• spectrum/line plot tool rewritten in HTML5
• line plots for HLSP images
• automatic adaptation of the footprint view for large or all-sky searches to show filtered sky area

Please see the HLA page (http://hla.stsci.edu) for further details. Updates will be posted as they become available.

New and Improved HUT Data

The Hopkins Ultraviolet Telescope (HUT) was an ultraviolet spectrograph that flew on the space shuttle in December 1990 and March 1995. It observed several hundred targets, ranging from Solar System objects to active galactic nuclei. The spectra were primarily obtained in HUT’s first spectral order, which covered 820–1850 Å with 3 Å resolution. Over 180 papers have been published using HUT data, and now a revised and improved pipeline has been used to reprocess the spectra. The new pipeline is described in detail by Dixon et al. (2013, PASP, submitted; see arXiv:1303.6131). The spectra are now stored as a time-tagged photon list similar to FUSE data, while extracted spectra (including orbital-night-only spectra when present) are also provided. The new data are in a user-friendly
Figure 6: Example of HUT preview image for the white dwarf H1504+65. **Top panel:** spectrum. **Middle panel:** count rate during the observation. **Bottom panel:** pointing errors. Times when the object was out of aperture due to jitter or less than 15° from the Earth’s limb are represented by shaded areas in the middle panel, while times corresponding to orbital day are denoted by a thick, black line at the top of the middle panel’s plot.
Figure 7: GALEX image of the nebula 30 Doradus, at the core of the Large Magellanic Cloud, available as part of the most recent GR7 deliverables.

format, are compliant with Virtual Observatory, and include easy-to-read preview plots of the spectra, count rates, and pointing errors. (Figure 6 shows a sample preview spectrum.) More information about HUT is available at the mission’s front page on MAST (http://archive.stsci.edu/hut/index.html). To search and download HUT data, see our search form, available from the same page, and don’t forget to make use of the plot previews to examine the spectra, available by clicking on the data ID of an observation in your search results table.

GALEX Archive: additional GR6 data and new GR7

GALEX has released another set of data to MAST, now available to the community through all of our active search interfaces. This release includes some previously unreleased tiles from GR6, which are now provided with updated co-additions. Also, new tiles (including near ultraviolet images and spectra) from GR7 are available, which include visits to the Galactic cap, areas near the Galactic plane, much of the Large and Small Magellanic Clouds, the Kepler field, and M31. A summary of these releases is found on the GALEX front page on MAST (http://galex.stsci.edu/). Users of GR7 data should carefully read the pipeline documentation page, available from this page, which describes important changes to the processing pipeline that account for a sun-related anomaly experienced by the spacecraft in May 2010 (http://www.galex.caltech.edu/wiki/Public:Documentation/Chapter_8). These changes to the data products and pipeline include the presence (and subsequent masking) of residual ghosts for bright objects, although such artifacts should be minimal in most cases. Users are encouraged to visit our interactive GALEX search site, GalexView (http://galex.stsci.edu/GalexView/), and our SQL-based CasJobs site (http://galex.stsci.edu/casjobs/) to access the new data. Updates on GALEX will continue to be posted on the aforementioned GALEX front page on MAST.

As always, please feel free to contact the MAST help desk (archive@stsci.edu) with questions, or contact us through Facebook (MAST Archive) or Twitter (@MAST_News) to provide suggestions on how we can improve our sites and services.
Every six months for the past three years, Hubble has been collecting images of the Andromeda galaxy (M31) as part of the Panchromatic Hubble Andromeda Treasury (PHAT) survey (Dalcanton 2011, Dalcanton et al. 2012). When the survey is completed in the summer of 2013, Hubble will have collected over 40,000 separate exposures of M31 taken over more than 800 orbits. Hidden in these images are ~3,000 star clusters, which is a larger sample than the star clusters known in the Milky Way. These clusters are invaluable laboratories which we will use to study the initial mass function of massive stars, constrain rare stages of stellar evolution, and learn about the transition of stars from bound clusters to dispersed field populations.

To achieve any of these science goals, we first need to find the star clusters. Following a long tradition of cluster finding, we started identifying clusters just by looking through the images ourselves. We hoped to follow this initial by-eye search with an automated search of the remaining data, using the visually identified sample as a training set for the algorithmic methods. Using the first year of data collected for PHAT, eight members of the cluster science team each spent about a month searching the first ~20% of the survey’s images, hunting for clusters. The team identified ~600 likely star clusters, a four-fold increase over the sample of previously known clusters within the same search region (Johnson et al. 2012). These results were very encouraging, and we were excited to expand our work to the rest of the PHAT survey data.

Despite our best efforts, however, our attempts at automated cluster identification came up short. Variations in cluster appearance due to differences in age, mass, spatial distribution, and vast changes in the galaxy background proved troublesome for objective identification techniques. We were unable to create an automated cluster-finding methodology that did not require significant amounts of human input. Without an automated algorithm, cluster identification became a major obstacle to progress. Our path to addressing our scientific questions now seemed to include many months of visual identification and confirmation of cluster candidates.

The birth of the Andromeda Project

To overcome this cluster-identification obstacle, we collaborated with the Zooniverse (www.zooniverse.org) to create a citizen science project called the Andromeda Project (www.andromedaproject.org). The goal of “citizen science” is to engage untrained individuals in real science projects, for the benefit of both researchers and volunteers. Citizen science isn’t just outreach; it is research that can be performed better or faster by tapping into the surplus of brain power on the web. The most famous of these projects is the Zooniverse’s well-known Galaxy Zoo, whose ~100,000 users have morphologically classified nearly one million galaxies (Lintott et al. 2011). The Zooniverse has since expanded into topics ranging from meteorology to animal behavior. It now involves a community of more than 750,000 citizen scientists—a powerful force for “crowd sourcing” scientific problems.

Our cluster-finding task was a good match to the strengths of citizen science. We benefited greatly from previous Zooniverse projects; the Andromeda Project site borrowed heavily from the Seafloor Explorer project’s interface, and a community of engaged citizen scientists interested in astronomy already existed, thanks to Galaxy Zoo and other previous projects. Once initiated, the project moved quickly. Planning started during the summer of 2012, development followed in mid-September, and beta testing of the site occurred in early November.

The Andromeda Project website is designed to get users doing science quickly. After taking a short tutorial on the basics of cluster identification and how to use the interface, users start classifying images immediately. While non-expert volunteers may not individually perform as well as members of our science team, combining large numbers of user classifications ensures high overall quality in the aggregate. In addition, we employ a number of cross-validation techniques to assign user weightings, which allows us...
to normalize user identifications based on the quality of an individual’s cluster selections. Using these analysis techniques, we expect the cluster catalog from the Andromeda Project to be very reliable.

One image per second

The Andromeda Project website was launched on December 5, 2012, with the goal of having 50 users examine each of ~12,000 cutouts from the PHAT images obtained over a period of a month or two. Thanks to press coverage, blog entries, social media, and email newsletters to the Zooniverse community, the Andromeda Project received ~7,000 unique visitors and more than 100,000 image classifications in the first day. This translates to an overall classification rate that is greater than one per second!

Although we expected a decline in the work rate after the initial excitement of the site’s launch died down, the rate of classifications remained high. This allowed us to conclude our data collection in an unexpectedly short amount of time. In just 16 days, we amassed over one million classifications, translating to more than 80 individual classifications per image. The volume of classifications, as well as the speed with which we were able to complete the work, surpassed all expectations.

In addition to the high-quality image classifications, the science team was quite impressed with the discussion that took place on the “Talk” page, the site’s interactive forum. The Andromeda Project participants were not only asking questions about cluster identification, but they were also asking insightful questions about the subsequent science that their work would enable. The forum provided an opportunity for the science team to interact with and educate the community that formed around the site. Watching an army of citizen scientists work on a project we were passionate about, and having them understand what it was they were doing, was an exciting and rewarding experience for all of us.

In a little more than two weeks, Andromeda Project participants had done work that would have taken our team of astronomers months to complete. Furthermore, initial results from the project, which we presented at the recent AAS meeting in Long Beach, show that these image classifications will lead to a high-quality cluster catalog. The spatial distribution of ~2900 star clusters from our initial catalog appear in Figure 1, and we show cutout images for a small selection of clusters in Figure 2. In fact, it appears that the new, crowd-sourced catalog is an improvement over our previous “expert” version, likely due to the factor of 20x increase in the number of views per search image provided by citizen scientists. While there is still much work to do, the Andromeda Project cluster catalog provides many promising avenues for cluster science in M31.

Please visit the Andromeda Project website (www.andromedaproject.org) and the project’s blog (http://blog.andromedaproject.org) for more information. The site will return this fall for a second round of data collection after final PHAT observations are taken this summer.

References

Dalcanton, J. 2011, Newsletter of the Space Telescope Science Institute, 28, No. 1

Figure 2: A gallery of star clusters in M31 identified as part of the Andromeda Project cluster search.
The Hubble Fellowship Program awards postdoctoral fellowships to candidates of exceptional research promise in astronomy and astrophysics. More than 310 of the most prominent and active scientists in the field have been supported at a crucial phase in their careers by the Hubble Fellowship Program, and the program continues to be one of the highlights of NASA's pursuit of excellence in space science. The program is presently in its 23rd year, and the impact of its "graduates" on the direction of astronomy and astrophysics in the U.S. continues to grow. Former Hubble Fellows can increasingly be found among the ranks of the faculty at college and university campuses and the professional staff of research institutions across the nation and beyond, as well as among the membership of prominent national advisory committees.

The scientific scope of the Hubble Fellows Program includes goals addressed by any of the missions in NASA’s Cosmic Origins Program. These missions presently include: Hubble Space Telescope, Spitzer Space Telescope, Stratospheric Observatory for Infrared Astronomy, Herschel Space Observatory, and James Webb Space Telescope. The program is funded by NASA and managed by the Institute. It is open to applicants of any nationality. Fellows may choose their host institution virtually anywhere in the U.S., subject to a maximum of one new fellow per institution per year. The duration of the fellowship is up to three years. More details are available at [http://www.stsci.edu/institute/smo/fellowships/hubble](http://www.stsci.edu/institute/smo/fellowships/hubble).

### Selection of the 2013 Hubble Fellows

The selection process begins with the recruitment of a selection committee, which is charged with providing a ranked list of the top ~10% of all applicants. Applications for the 2013 Hubble Fellowship Program were accepted through November 5, 2012, and the 2013 selection committee began its work shortly thereafter. The committee met at the Institute on January 17–18, 2013, to consider the 283 applications received by the deadline. Prof. Pieter Van Dokkum (Yale) chaired the 18-member committee of expert researchers from the astronomical community. As in previous years, the selection criteria were based primarily on the scientific excellence of the research proposals, and also as in previous years the high quality of the applicant pool made it difficult for the committee to identify the most outstanding candidates. Offers were made to short-listed candidates in early February, and the 17 new Hubble Fellows (see Table 1) are set to take up their fellowships in the fall of 2013.

### Table 1: Hubble Fellows appointed for fall 2013

<table>
<thead>
<tr>
<th>2013 HUBBLE FELLOW</th>
<th>Ph.D. INSTITUTION &amp; YEAR</th>
<th>HOST INSTITUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rachel Bezanson</td>
<td>Yale University – 2013</td>
<td>University of Arizona</td>
</tr>
<tr>
<td>Francesca DeMeo</td>
<td>Observatoire de Paris – 2010</td>
<td>Harvard College Observatory</td>
</tr>
<tr>
<td>Ruobing Dong</td>
<td>Princeton University – 2013</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>Jacqueline Faherty</td>
<td>The State University New York, Stony Brook – 2010</td>
<td>Carnegie Institute of Washington, Department of Terrestrial Magnetism</td>
</tr>
<tr>
<td>Renyu Hu</td>
<td>Massachusetts Institute of Technology – 2013</td>
<td>Jet Propulsion Laboratory*</td>
</tr>
<tr>
<td>Andreas Kuepper</td>
<td>Universität Bonn – 2011</td>
<td>Columbia University</td>
</tr>
<tr>
<td>Emily Levesque</td>
<td>University of Hawaii – 2010</td>
<td>University of Colorado, Boulder</td>
</tr>
<tr>
<td>Adam Miller</td>
<td>University of California, Berkeley – 2013</td>
<td>Jet Propulsion Laboratory*</td>
</tr>
<tr>
<td>Philip Muirhead</td>
<td>Cornell University – 2011</td>
<td>Boston University</td>
</tr>
<tr>
<td>Ondrej Pejcha</td>
<td>Ohio State University – 2013</td>
<td>Princeton University*</td>
</tr>
<tr>
<td>Pier-Emmanuel Tremblay</td>
<td>Université de Montréal – 2011</td>
<td>Space Telescope Science Institute</td>
</tr>
<tr>
<td>Jonathan Trump</td>
<td>University of Arizona – 2010</td>
<td>Penn State University</td>
</tr>
<tr>
<td>Daniel Weisz</td>
<td>University of Minnesota – 2010</td>
<td>University of California, Santa Cruz*</td>
</tr>
<tr>
<td>Jessica Werk</td>
<td>University of Michigan, Ann Arbor – 2010</td>
<td>University of California, Santa Cruz*</td>
</tr>
<tr>
<td>Zhaohuan Zhu</td>
<td>University of Michigan, Ann Arbor – 2011</td>
<td>Princeton University*</td>
</tr>
<tr>
<td>Adi Zitrin</td>
<td>Tel Aviv University – 2012</td>
<td>California Institute of Technology</td>
</tr>
</tbody>
</table>

* These institutions have accepted two new Hubble Fellows in 2013, and are therefore ineligible to host a Hubble Fellow in 2014.
The 23rd annual Hubble Fellows Symposium was held at the Institute on March 4–6, 2013. These symposia provide an occasion for the Hubble Fellows to discuss their research and to meet face-to-face with other Hubble Fellows and with the scientific and administrative staff who manage the program (Figure 1). This year the Institute was forced to close owing to inclement weather on Wednesday March 6, and the last sessions of the Symposium were held in a meeting room of the Colonnade Hotel. The program, slide presentations, and all recorded video (except for Wednesday March 6) are available at: https://webcast.stsci.edu/webcast/archive.xhtml.

A complete list of Hubble Fellows since 1990 is available at: http://www.stsci.edu/institute/smo/fellowships/hubble/fellows-list
What U. S. politician most passionately promoted astronomy? The answer must be John Quincy Adams (JQA). As historian Samuel Flagg Bemis writes of our sixth president (1825–1830):

A scholar in the White House is a pleasing image, if not too frequent a fact of American history. During the nineteenth century, after the passing of the talents of the Revolution, there was only one American President who was a notable sponsor of learning: that was John Quincy Adams. He continued the role even more strongly during his public service after he left the White House.

The long winter nights of four years at the Court of St. Petersburg sharpened an interest in the mysteries of the firmament that sparkled so mightily over the vast realm of Russia, and he began to study astronomy. His curiosity about the movements of the heavenly bodies continued during the peaceful years of his London mission in the idyllic residence at Ealing, hard by the Meridian of Greenwich. He made himself familiar with the works of Newton, Schubert, Lalande, Biol, and Lacroix and other standard treatises of the day. Astronomy and mathematics appeared to him as the keys that would somehow unlock illimitable reaches of science and its application to human welfare.

President John Quincy Adams, with his developing interest in science, tried to take the lead in his program for...the physical and moral improvement of mankind, including advancement of knowledge and learning. For such a program a national university and a national observatory seemed like noble and shining instruments..."1

In 1823, John Quincy Adams (JQA) pledged $1000 to Harvard University to fund a professorship of astronomy and an observatory, which opened at last in 1839 with JQA serving on the committee of the Board of Overseers that supervised it.2 The 15-inch “Grand Refractor” of Harvard College Observatory would see first light 1847.

In 1825, in his first annual address to the Congress, JQA proposed a national observatory:

Connected with the establishment of a university, or separate from it, might be undertaken the erection of an astronomical observatory, with provision for the support of an astronomer, to be in constant attendance of observation upon the phenomena of the heavens; and for the periodical publication of his observations. It is with no feeling of pride, as an American, that the remark may be made that, on the comparatively small territorial surface of Europe, there are existing upward of one hundred and thirty of these lighthouses of the skies; while throughout the whole American hemisphere there is not one. If we reflect a moment upon the discoveries which, in the last four centuries, have been made in the physical constitution of the universe by the means of these buildings, and of observers stationed in them, shall we doubt of their usefulness to every nation? And while scarcely a year passes over our heads without bringing some new astronomical discovery to light, which we must fain receive at second-hand from Europe, are we not cutting ourselves off from the means of returning light for light, while we have neither observatory nor observer upon our half of the globe, and the earth revolves in perpetual darkness to our unsearching eyes?3

Arguably, JQA's dream of a federally funded observatory to serve the nation with bountiful discoveries—to return light for light—was only fully realized in the twentieth century, by the NSF's National Optical Astronomy Observatory and NASA's Great Observatories.

In 1825, JQA's political opposition mocked his lofty ideas about federal funds for science by twisting his metaphor—"lighthouses of the skies"—into the fantastical "lighthouses in the skies."4 One might hear in these words an unconscious and unwitting anticipation of space telescopes—"houses" of astronomical light in space.

After the White House, in his later years, JQA's passion for astronomy never ebbed, and he found new avenues to pursue it.

JQA was elected to the House of Representatives for eight two-year terms, starting in 1830. For ten of these years, he chaired special subcommittees struggling to deal with the bequest by James Smithson of his entire fortune "to the United States of America, to found at Washington, under the name of the Smithsonian Institution, an Establishment for the increase & diffusion of knowledge among men."
In 1840, in his second report on the Smithsonian fund, JQA advocated a national observatory, explaining:

The express object of an observatory is the increase of knowledge by new discovery. The physical relations between the firmament of heaven, and the globe allotted by the Creator of all to the abode of man, are discoverable only by the organ of the eye. Many of these relations are indispensable to the existence of human life, and, perhaps, of the earth itself. Who can conceive the idea of a world without a sun, but must connect it with the extinction of light and heat, of all animal life, of all vegetation and production; leaving the lifeless clod of matter to return to the primitive state of chaos, or to be consumed by elemental fire? The influence of the moon—of the planets, our next door neighbors of the solar system—of the fixed stars, scattered over the blue expanse in multitudes exceeding the power of human computation, and at distances of which imagination herself can form no distinct conception; the influence of all these upon the globe which we inhabit, and upon the condition of man, its dying and deathless inhabitant, is great and mysterious, and, in the search for final causes, to a great degree inscrutable to his finite and limited faculties. The extent to which they are discoverable is, and must remain unknown; but, to the vigilance of a sleepless eye, to the toil of a tireless hand, and to the meditations of a thinking, combining, and analyzing mind, secrets are successively revealed, not only of the deepest import to the welfare of man in his earthly career, but which seem to lift him from the earth to the threshold of his eternal abode; to lead him blindfold up to the council chamber of Omnipotence; and there stripping the bandage from his eyes, bid him look undazzled at the throne of God. 5

JQA walked the walk as well as he talked the talk. In October–November 1843, at 76 years of age and in poor health, JQA traveled through rain and cold, by train, steamer, horse-drawn canal boat, and stagecoach, to dedicate the pier of the Cincinnati Observatory, the first public observatory in America. In 1845, on the occasion of first light in the 12-inch refractor, the founder, Ormsby Mitchel, would remark, “The building of the Cincinnati Observatory has forever settled the great question as to what a free people will do for pure science.” 6

JQA died in the U.S. Capitol on February 23, 1848. His last words were, “This is the end of earth, but I am composed.” 7 He had good reason to be content about his contributions to American astronomy, which prefigured all our national observatories of—and in—the sky.

Notes

2 Ibid., 514
3 John Quincy Adams, First Annual Message (Dec. 6, 1825), in 2 A Compilation of the Messages and Papers of the Presidents 299–317 (James D. Richardson ed., Washington, Gov’t Printing Office 1897)
4 Bemis, loc. cit., 503
7 Bemis, loc. cit., 536
This image of the Horsehead Nebula has been photographed by Hubble in infrared light to mark its 23rd anniversary. In this image, the backlit wisps along the Horsehead’s upper ridge are being illuminated by Sigma Orionis, a young five-star system just out of view. Along the nebula’s top ridge, two fledgling stars peek out from their now-exposed nurseries.

Scientists know a harsh ultraviolet glare from one of these bright stars is slowly evaporating the nebula. Gas clouds surrounding the Horsehead already have dissipated, but the tip of the jutting pillar contains a slightly higher density of hydrogen and helium, laced with dust. This casts a shadow that protects material behind it from being stripped away by intense stellar radiation evaporating the hydrogen cloud, and a pillar structure forms. Image credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
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Nial Tanvir (Co-Chair) University of Leicester, nrt3@star.le.ac.uk

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Adam Burgasser, University of California – San Diego  Giampaolo Piotto, University Padova
Jane Charlton, Penn State University  Ata Sarajedini, University of Florida
You-Hua Chu, University of Illinois – Urbana  Brian Siana, University California – Riverside
Drake Deming, University Maryland  Ann Zabludoff, University of Arizona, Steward Observatory

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<td>23 May 2013</td>
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<tr>
<td>Cycle 21 Notifications</td>
<td>24 May 2013</td>
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<td>STIC meeting</td>
<td>12–13 June 2013</td>
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<td>Phase II proposals/budgets due</td>
<td>27 June 2013</td>
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<td>Science Working Group</td>
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<tr>
<td>Financial Review Committee meeting</td>
<td>Mid-August 2013</td>
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<td>Cycle 21 begins</td>
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