The James Webb Space Telescope—It’s Complicated, but so Is Leadership

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The recent release of NASA’s Independent Comprehensive Review Panel report (the Casani report) on the James Webb Space Telescope (JWST) has understandably caused consternation within the community, and some of our colleagues’ sound-bite quotes decrying the state of space astrophysics were quickly circulated in the press and on the Internet. As the dust has settled, it’s important to step back for a moment to reflect on why we want to build such an audacious telescope. The words of the President of the AAS, Debra Elmegreen, in a recent article in Space News bear repeating, “We all need to recognize that JWST and the initial $5 billion investment cannot be allowed to fail, since so much of future astrophysics research was built upon the foundation it was to provide—as the Casani report concludes, JWST will play a key role in understanding how and when the first galaxies were born, characterizing the planets that are now being discovered around nearby stars, in providing further insights into the nature of the dark energy and dark matter, and into how stars and planetary systems are born. There is no easy path to understanding such complex scientific questions. To do these things at the level needed to advance scientific understanding requires a complex telescope with truly unique capabilities. JWST is that telescope.” (Space News, “American Leadership in Astrophysics at Risk,” 22 November 2010.)

I came to the Space Telescope Science Institute because of JWST. Even though I helped to build two large ground-based telescopes, I recognized that there are astronomical observations we struggle to do from the ground. For example, even with 8-m or 10-m telescopes it is next to impossible to take the spectra of high-redshift galaxies to understand the star-formation processes a billion years after the Big Bang. The same is true when trying to measure distant ($z > 1$) supernovae to try and unravel Dark Energy—it’s a really tough measurement from the ground. As is mapping dust emission to uncover telltale trails of young planetary systems; this is proving to be difficult even in the closest systems. My colleagues who built the Hubble and Spitzer space telescopes similarly realized that to take the next steps in exploring the Universe would require a bigger space telescope. There is no mystery why: observational astrophysics is a photon-limited field, and once you have near perfect detectors (as we do), our only free parameters are either to spend millions of seconds on every observation or to increase the aperture of the telescope. A large-aperture space telescope combined with the low backgrounds found at L2 was the basic design rationale for JWST, and the broad science this telescope enables was compelling enough to make it the highest-priority large space mission of the 2000 Decadal Survey on Astronomy and Astrophysics.

A decade later, even as our scientific expectations have evolved since the original science case was written—as the Casani report itself notes—JWST remains the most scientifically powerful telescope NASA, ESA and CSA will ever have built: “the next Great Observatory to replace the Hubble Space Telescope.” A decade ago, we were just coming to terms with the possibility of Dark Energy. With JWST, we will reach back to the beginning of time to detect very early supernovae and break the possible degeneracy between supernova evolution and Dark Energy. A decade ago, we had not yet begun to measure the constituents of exoplanetary atmospheres with transit spectroscopy using Hubble and Spitzer. With JWST, we will use the same technique; as the recent 2010 Decadal Survey (New Worlds, New Horizons in Astronomy and Astrophysics; NWNH) recognized, JWST will be “a premier tool for studying planets orbiting stars that are smaller and cooler than the Sun.” The goal of detecting liquid water on a planet close to the size of Earth, in the habitable zone around another star, may be within the reach of JWST. As NWNH notes, with JWST “the era of study of … cousins of the Earth … is underway.”

And this does not include the great unknown territory that will be uncovered when we fly a telescope 100 times...
more sensitive than Hubble, almost 1000 times more sensitive than Spitzer. Imagine the creative energy unleashed by the roughly 8,000 astronomers who currently use Hubble and Spitzer. According to a White Paper submitted to NWNH (Sembach et al. 2009), over the period 2005–2007, the Spitzer and Hubble programs alone generated over $130M in General Observer grants, and this community published over 3,000 papers based on Hubble and Spitzer data. JWST is the next Hubble, the next Spitzer—that’s why we are building this ambitious telescope.

It is true JWST has confronted us with some seriously tough technological challenges: how to build a telescope 65% the size of the W. M. Keck telescope, but reduce its mass by almost two orders of magnitude compared to a ground-based telescope; how to find a way to package it so it could be launched on an Ariane 5 rocket and deployed a million miles from Earth; and how to operate it at 40K. It’s been very hard to manufacture 18 beryllium mirrors that can hold their figures to better than 20 nanometers at cryogenic temperatures, or build a deployable gossamer-like sunshield the size of a tennis court. But we have. The Casani report recognized these technological achievements: “a substantial amount of cutting-edge hardware has been delivered and is now being tested as part of the first steps toward the overall integration and test of the Observatory.” We are not looking at a trail of technological failures or wasted resources. In fact, what we see is a series of “solved problems” on the complex and difficult journey to build the most powerful space telescope launched by any space-faring nation.

A few weeks ago, The New York Times ran an obituary of Joseph Gavin, who designed and built the lunar lander. It drew me back to an earlier era, where doing difficult things in space defined a nation and a generation. The Times quoted Gavin as saying, “If a project is truly innovative, you cannot possibly know its exact cost and exact schedule at the beginning…and if you do know the exact cost and the exact schedule, chances are that the technology is obsolete.” The Casani report echoed these words: “from 2002 to 2008, JWST struggled with several cutting-edge developments. These developments took longer and consequently cost more than forecast.”

Let us remind ourselves it was very hard to build the Hubble Space Telescope. But we did. Today Hubble supports thousands of astronomers worldwide, and continues to inspire the public and a new generation of school children with its images of breathtaking beauty.

Now we are again struggling with the consequences of doing something no one has done before. Those of us who have built machines like large telescopes have experienced the myriad ways that unpredictable problems emerge from new technologies, challenging engineering, and the complicated logistics of putting complex things together.

The JWST project needs to do better, and the Casani report articulates what needs to be changed. NASA and the Project Team have committed to learning these lessons and regaining the trust of both those who have advocated for JWST and the tax-payers who have funded JWST. But I don’t see an astronomers’ hurricane, leaving devastation in its wake. I see a community willing to take risks on behalf of science, so we can extend the scientific frontiers and do things no one has done before. I see that building a state-of-the-art machine for science is in the end an inherently complex and tremendously imperfect human endeavor. The cover letter to the Casani report on why JWST should go forward finished on a famous quote from the dawn of the Space Age, “…we do these things and others, not because they easy, but because they are hard.” To finish President John F. Kennedy’s quote: “…because that goal will serve to organize and measure the best of our energies and skills; because that challenge is one that we are willing to accept, one we are unwilling to postpone.”

In the end, someone has to provide “the next Hubble” to the next generation. If not us, then who?

“… And this does not include the great unknown territory that will be uncovered when we fly a telescope 100 times more sensitive than Hubble, almost 1000 times more sensitive than Spitzer. Imagine the creative energy unleashed by the roughly 8,000 astronomers who currently use Hubble and Spitzer.”
The Scientific Impact of Webb

The U.S. astronomical community recently completed the Astro 2010 decadal survey. The Astro 2010 report outlines the top research questions for the coming ten years, and presents a vision of the facilities best suited for accomplishing the science. This vision includes huge advances in sensitive, wide-field imaging at optical and infrared wavelengths, as well as the means to characterize new discoveries spectroscopically. Among Astro 2010’s most compelling scientific priorities are (1) searching for the first stars, galaxies, and black holes, which formed when the universe was in its infancy, (2) exploring nearby stars for life-bearing planets like Earth, and (3) testing fundamental physics in cosmic regimes, which could modify scientific principles accepted today.


Ten years ago, the 2000 decadal survey gave the James Webb Space Telescope its top priority, and Astro 2010 did not re-rank it. Correspondingly, the Astro 2010 results amply confirm that Webb’s unique capabilities are essential to the freshly framed scientific agenda. Throughout the committee and panel reports, as well as the working documents, the Webb being built today is allied and synergistic with the missions that will be developed tomorrow. Their alliance convincingly addresses the scientific goals. For example, ALMA will detect dust and gas that is associated with the first bursts of star formation, and Webb imaging will be sensitive to the first light from stars and galaxies at these formation sites. Similarly, optical and infrared surveys such as with the Large Synoptic Survey Telescope and Wide Field Infrared Survey Telescope will yield new populations of intermediate- and high-redshift galaxies, systems that will be studied with Webb spectroscopy, to map star formation histories and abundances over cosmic time.

The Webb Mirrors are Wearing their “Bling”

The Webb mission successfully achieved several milestones in recent months. Eight flight mirrors were coated with gold—the first six primary mirror segments, and the secondary and tertiary mirrors. Optical engineers at Ball Aerospace confirmed that the reflectivity of witness samples met requirements. After the flight mounts were attached to the mirrors, cryogenic measurements at the Marshall Space Flight Center’s X-Ray and Cryogenic Facility showed no significant distortions due to the coatings. This demonstration clears the manufacturing path for the remaining 12 primary segments and spares. Because of ongoing process improvements, Ball Aerospace predicts that all of the flight-ready segments will be delivered by summer 2011, completing a seven-year development process.

Webb Instruments

Development of all four Webb instruments continues, full speed ahead. The European Space Agency’s Near-Infrared Spectrometer (NIRSpec) will soon undergo pre-shipment testing. At EADS Astrium, in Germany, engineers have assembled the flight model, complete with the micro-shutter array and mercury-cadmium-telluride detectors. In the next months, the instrument will undergo functional and environment testing. Then it will be delivered to Goddard Space Flight Center for installation in the integrated science instrument module.

Can’t Wait to Fly

The Webb integration and test program is complicated. It requires multiple cryogenic tests of major components as they are integrated into the observatory and readied for launch. Each test requires
weeks to cool the science instruments and/or primary mirror optics to the planned operating temperature (~40 K) and more weeks to bring them safely back to room temperature. Searching for ways to reduce the cost and duration of testing, NASA created a team—the Test Assessment Team (TAT), which included several astronomers—to review the baseline test plan and make suggestions for streamlining it. Many suggestions were gathered during informal meetings of the development contractors and NASA project. The TAT recommended that only the highest priority tests, including checks of workmanship and confirmations that the observatory will operate in orbit, be mandatory. Other tests should be simplified without jeopardizing the mission, and, if possible, be done in parallel with the major test flow. The project has accepted most of the team’s recommendations and drafted a revised test program for the 2011–2015 budget process. The TAT report can be downloaded in its entirety at http://www.jwst.nasa.gov/publications.html.

Figure 3: The grating wheel assembly mounted on the NIRSpec flight model (ESA, EADS Astrium).

Flux Calibration Standards for Webb

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Flux calibrations in physical units are required to compare observational results with physical models of observed objects. For example, one incentive for accurate absolute flux standards is the need to measure the relative fluxes of red-shifted supernovae (SNe) type Ia spectra in their rest frame. Cosmological parameters derived from SNe Ia observations specify the nature of dark energy and the acceleration of the expansion rate of the universe. The constraints on these parameters are most significant when the relative flux versus wavelength is known to an accuracy of 1% or better. Precise flux calibrations are also needed to accurately measure the Hubble constant using Cepheid variables.

The Institute anticipates that a variety of important science programs of the James Webb Space Telescope will rely on high-quality flux calibrations. For that reason Institute staff are developing a set of stellar spectral energy distributions (SEDs) to facilitate the transfer of the flux calibration to Webb science targets.

The Webb instrument complement comprises Mid-Infrared Instrument (MIRI; 18 modes), Near-Infrared Camera (NIRCAM; 8 modes), Near-Infrared Spectrometer (NIRSPEC; 7 modes), and Tunable Filter Instrument (TFI; 8 modes). These instruments have a wide dynamic range of sensitivity over their combined wavelength coverage of 0.6–30 microns.

Absolute flux calibrations of spectrometers and photometers are normally derived from observations of standard stars with well-known SEDs. Figure 1 shows a sample of SEDs from our Webb standard-star library, along with the range of sensitivities for NIRCam imaging and MIRI imaging and coronagraphy. Each of the standards is established by fitting a model atmosphere to pedigreed Hubble fluxes. The SED beyond the 1-micron limit of Space Telescope Imaging Spectrograph (STIS) or, in some cases, beyond the 2.5-micron limit of Near Infrared Multi-Object Spectrometer (NICMOS), depends on the fidelity of the model atmospheres used to make the best fits at the shorter wavelengths.

Sets of standard stars in two brightness ranges suffice to establish all infrared flux calibrations for the four Webb instruments. A selection of at least three stellar types avoids systematic effects that might occur in modeling only one type. To minimize the complication of molecular species in the models, the three stellar types are early G solar analogs (Bohlin 2010), early A (Bohlin & Cohen 2008), and white dwarf (WD) stars. The A and G stars are the primary standards for Spitzer (Rieke et al. 2008), while the WDs are the primary standards for Hubble (Bohlin et al. 2001). Whenever stars brighter than any known WD are required, OB stars are used instead of WDs. If all three types yield the same Webb instrumental sensitivities, then a precision at the level of agreement can be claimed.

Assuming that the systematic errors in modeling are uncorrelated from star to star, a bare minimum of four stars of each type and in each mode will reduce the 1–2% statistical uncertainty in the modeling process to a <1% error in the mean. To withstand the usual 20–30% attrition of the proposed standards
Figure 1: The NIRCam (left) and MIRI (right) sensitivity limits and the spectra of the proposed primary calibrators are shown with blue for WDs, green for A types, and red for G stars. The vertical bar—where the min, middle, and max marks indicate the min full frame, max full frame, and max subarray sensitivities, respectively—gives the sensitivity in each filter. A Kurucz model for Vega that matches the observed STIS flux below 1 micron has been included to illustrate that MIRI can observe very bright targets at the longest wavelengths.

by unforeseen problems, such as unknown companions, model deficiencies, or stellar variability, five candidate targets are required, as summarized in our suggested list, in Table 1.

For all Hubble instruments, the pedigree of the flux calibrations is traceable to three primary WD standards G191B2B, GD71, and GD153, where the slopes of the SEDs are determined by calculations using non-local thermodynamic equilibrium (NLTE) models and the TUSTY code for pure hydrogen atmospheres. The temperature and gravity are determined by fitting the models to ground-based observations of the Balmer line profiles.

While the three primary hot WD NLTE models set the slope of the measured SEDs, the absolute flux of these three primary standards is set by the STIS measurements of Vega relative to the WDs, along with the absolute flux for Vega of $3.46 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ ± 0.7% at 5556 Å (Mégessier 1995). The bandpasses of the absolute spectrophotometry used to establish this monochromatic flux of Vega range from 10 to 100 Å.

Work is in progress to measure any offsets between these Hubble-based fluxes and independent absolute flux measurements in the infrared. In particular, new Spitzer Space Telescope observations of WDs, A stars, and solar-analog G stars were made near the end of the cold mission in the four bands of the Infrared Camera (Reach et al. 2005). These new observations are supplemented by more data sets for the same stars from the Spitzer archive. Preliminary results indicate that our Hubble fluxes in the IR are ~1% lower than the official IRAC calibration of Reach et al. 2005 and 1.5% lower than the proposed calibration of Rieke et al. (2008). A more robust result will be possible when new Hubble measurements of all the stars in Table 1 are modeled and compared to independently determined infrared SEDs.
# References


## Table 1: Current Webb Prime Calibrators

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*Already modeled to 30 microns with a SED available at [http://www.stsci.edu/hst/observatory/cdbs/calspec.html](http://www.stsci.edu/hst/observatory/cdbs/calspec.html)
Diffraction-limited telescopes in space demand high pointing stability to ensure sharp images. Great effort and expense was paid to ensure the quality of *Hubble* images— with outstanding success, due to the low jitter when *Hubble* is locked onto guide stars. Now, as we plan operations for the *James Webb Space Telescope*, we are drawing on the *Hubble* experience to ensure the efficient selection of guide stars to stabilize *Webb*’s pointing.

*Hubble* has three fine guidance sensors (FGSs). Their fields of view (FOVs) arc around the apertures of the other science instruments. *Hubble* observes pairs of guide stars simultaneously, with each star in the FOV of a different FGS. The typically long FGS-to-FGS lever arms allow *Hubble*’s pointing control system to tightly control the telescope’s roll around the line of sight, as well as the transverse pitch and yaw.

On Webb, there are two FGS FOVs, which are more centrally located than on *Hubble* (see Figure 1). The short FGS-to-FGS lever arm would not be effective in controlling the roll of the telescope, and therefore *Webb* uses separately mounted star trackers to control roll. The *Webb* attitude control system uses the FGSs in closed-loop mode to control the telescope’s pitch and yaw. Thus, only one guide star is needed for the fine guiding of *Webb*.

The *Webb* FGS is a dual-channel, near-infrared camera (like NIRCam) with two adjacent 2.4’ × 2.4’ FOVs. Each focal plane array is a 2048 × 2048 mercury-cadmium-telluride sensor-chip assembly. The central 2040 × 2040 pixels are sensitive to light, while the four outermost rows and columns are reference pixels, for bias measurements. The *Webb* FGS has neither a shutter nor a filter wheel.

The *Webb* FGS operates with a pass band from ~0.6 to 5 microns. The camera can reach 58 µJy at 1.25 µm (*J* = 18.6) in 63 milliseconds using in 8 × 8 pixel sub-arrays. This combination of sky coverage and sensitivity ensures that the FGS will be able to meet the requirement that it have a 95% probability of finding a useful guide star in the range 12.1 ≤ *J* ≤ 18.6 anywhere on the sky, even at sparsely populated, high galactic latitudes.

**Webb Guide Star Identification & Acquisition**

The following is a description of the *Webb* guide star identification and acquisition process.

In preplanning, the user has specified the science target and the instrument aperture. These constraints, as well as any restrictions on the attitude of the spacecraft, determine the positions on the sky of the FGS FOVs on any given date. Within these FOVs, the guide star catalog will identify up to three valid guide star candidates and up to ten reference objects for use in guide star identification. Valid guide stars must meet pre-defined criteria regarding magnitude, magnitude uncertainties, limits on the background, and size/shape requirements. Valid guide stars must have a flux brighter than 58.0 µJy and fainter than 23 mJy at 1.25 µm. When the time for the observation arrives, *Webb* slews to the preplanned attitude for guide star identification, and the FGS takes a full-frame image. The FGS flight software seeks to match the observed pattern of sources with the cataloged positions and magnitudes of guide stars and reference objects. If the identification of a guide star fails, the next guide star candidate is tried. The planned availability of up to three guide star candidates per visit dramatically reduces the risk of failing to acquire any guide star at all.

Assuming the identification of the guide star succeeds, its centroidal position in the FGS FOV is repeatedly calculated from images taken in increasingly small sub-arrays. Initially, these centroids are calculated using a 128 × 128 pixel sub-array (8.8’’ × 8.8’’). Then, the sub-array is reduced to 32 × 32 pixels (2.2’’ × 2.2’’). At that point, the FGS enters closed-loop pointing control with the attitude control system, with guide star centroids reported at 16 Hz. Next, the telescope maneuvers to position the guide star in the FGS FOV such that the science target is placed at the desired location in a science aperture. (The FGS is required to have a probability >99.8% of acquiring any valid guide star after a successful identification.)
Once locked in position, the FGS uses an 8 × 8 pixel (0.6” × 0.6”) sub-array to track the guide star during the observations. In fine-guide mode, the absolute pointing accuracy requirement of Webb with respect to the celestial coordinate system will be 1” (1-σ, per axis). The relative errors between pointings after small slews with the same guide star between different exposures and visits for the same field, will be 0.005” (1-σ, per axis).

The Webb Guide Star Catalog

The Webb ground system will select guide stars and reference objects for Webb observations from the Guide Star Catalog II (GSC-II) and the Two Micron All Sky Survey (2MASS) Point Source Catalog (AJ, 136, 735L; AJ, 131, 1163). Even though the GSC-II, which was developed for Hubble, is based on a photographic survey, it is the best sources of guide stars for Webb. This is because GSC-II is the deepest and most complete all-sky survey available. For example, it is 70% complete at $J = 18.6$. GSC-II contains approximately a billion objects (~0.3 billion stars), which were observed in three photographic pass bands: $B_J$ ($\lambda_{\text{eff}} = 0.47 \mu \text{m}$), $R_J$ ($\lambda_{\text{eff}} = 0.64 \mu \text{m}$), and $K_S$ ($\lambda_{\text{eff}} = 0.85 \mu \text{m}$).

The 2MASS point-source catalog contains 0.47 billion objects over the entire sky in the $J(1.25 \mu \text{m})$, $H(1.65 \mu \text{m})$, and $K_S(2.16 \mu \text{m})$ band passes. The resolution (≥ 2”) of the 2MASS data is not sufficient to ensure that a given object is truly a point source. Sources at the bright end of the catalog ($J < 12.1$) are too bright for guiding, and the faint limit of the catalog ($J = 17$) is brighter than the expected faint limit for Webb FGS guide stars. According to previous studies, the 2MASS point source catalog is complete and has a contamination fraction of <10% down to $J = 16$.

The on-board guide star identification and acquisition process utilizes a small local star catalog, provided by the ground system. This catalog contains the expected positions and predicted detector count rates of the guide star and reference objects found in the FGS FOV. Because the FGS is a broadband camera with a wavelength range of ~0.6 μm to 5.0 μm, the magnitudes of the GSC-II objects—$B_J$, $R_J$, and $K_S$—must be transformed into $J$, $H$, $K_S$ if 2MASS magnitudes are not available, and then extrapolated from $K_S$ to 5 μm. These optical and NIR fluxes are then convolved with the telescope aperture and multiplied by the FGS throughput and detector responsivity to derive the predicted electron count rate.

Transformations of the GSC-II optical magnitudes into the near infrared $J$, $H$, and $K_S$ have been derived from color-color diagrams for stars common to both GSC-II and 2MASS. The accuracy of these transformations was confirmed using stars common to both GSC-II and the UKIRT Infrared Deep Sky Survey’s Large Area Survey (UKIDSS/LAS) catalog, which goes deeper than the faint limit of the FGS (http://www.ukidss.org).

At high galactic latitudes ($|b| > 45$ degrees), where only 48% of GSC-II stars have 2MASS matches within 1.75”, the effects of reddening are negligible. Consequently, the magnitude transformations are fairly accurate. At low galactic latitudes ($|b| < 30$ degrees), where highly variable reddening hinders accurate magnitude transformations and the GSC-II catalog is subject to confusion, 87% of GSC-II stars have 2MASS matches within 1.75”, eliminating the need to predict their NIR magnitudes.

Guide Star Selection Criteria

The Webb guide star selection criteria are still being developed. To date, several guide star studies have been undertaken, resulting in the conclusions below.

Brightness. Guide stars must have a flux greater than 5.8 mJy and less than 23 mJy at 1.25 μm—roughly the magnitude range 12.1 ≤ $J$ ≤ 18.6. These limits ensure that the measurements of the image centroid will be reliable. The predicted FGS count rate should be greater than 100 e−/second.

Isolation. Guide stars must have no neighbors of comparable brightness within 4”.

Classification. GSC-II contains a star/non-star classifier for each object. Valid guide stars must be classified as stars. For reference objects, we are studying the possible use of non-stars. At high galactic latitudes $|b| > 30^\circ$, the number of non-stars in GSC-II can outnumber the stars by a factor of three to four. Moreover, on average, there will be only ~3 stars in the identification image, along with several times more objects classified as non-stars. For approximately 20% of the FGS fields, there will be only one GSC-II star among several non-stars. Furthermore, if non-stars are not provided as
reference stars, their prevalence could overwhelm and defeat the guide star identification algorithm for regions on the sky away from the disk of the Galaxy.

**Measures of size and shape.** The GSC-II catalog contains measurements of the semi-major axis and eccentricity for each cataloged object. Independent measurements of the sizes and shapes of GSC-II objects, based on images from *Hubble’s Advanced Camera for Surveys* Wide Field Channel, found the GSC-II size and shape measures to be largely unreliable. This finding is not surprising; recall that the GSC-II is based on photographic plates, on which brighter objects, even point sources, appear larger while fainter objects appear smaller. While the semi-major axis and eccentricity measures in GSC-II are each unreliable taken alone, the combination of large semi-major axis and large eccentricity is a reliable indicator that a star is not suitable for guiding.

Studies have found that the vast majority of all GSC-II objects are very compact. *Hubble* measurements indicate that most of both the stars and non-stars have full-width at half-maximum less than 0.2″, and *Source Extractor* flux radii < 0.1″. With radii this small, the non-star objects will be nearly indistinguishable from stars to the FGS flight software as it interrogates the guide star identification image. Furthermore, the identification image will be taken in coarse-guiding mode, subject to 0.1″/second drift rates (1-σ) in pitch and yaw. (The identification image exposure times are on the order of 0.7 seconds.)

**GSC-II detections.** The magnitude transformation required to predict FGS count rates was found to be less accurate for GSC-II objects without photometry in the *I* band. As a result, candidate guide stars lacking a GSC-II *I*-band measurement will be passed over if a star is available for which the \((B_J, I_N)\)-based transformation can be applied.

Approximately 5% of GSC-II entries, mostly near the faint limit of the pass bands, are thought to be catalog artifacts. If an object was detected in more than one pass band, it is less likely to be a catalog artifact. If other guide star candidates are available, GSC-II stars with single-band photometry will be avoided in the guide star selection process. Likewise, stars detected on two or more GSC-II plates are more desirable than stars detected on only one plate.

**Guide Star Considerations in Designing and Visualizing Webb Proposals**

*Webb* programs can be designed and specified using the *Astronomer’s Proposal Tool* (APT), which is a software suite used for *Hubble* Phase I, Director’s Discretionary, and Phase II proposal preparation and submission. The suite contains an integrated set of tools for designing proposals, assessing the feasibility and schedulability of observations, bright object checking, querying the *Hubble* archive, diagnosing and reporting, and viewing specified exposures. Some prototypes of the capabilities for creating *Webb* proposals are already available in APT.

From within the APT environment, *Webb* proposals may be displayed in *Aladin*, which is an interactive tool for visualizing astronomical images, catalogs, and databases (2000A&AS.143.33B). *Aladin* displays *Webb* FOVs and GSC2 data.

*Aladin’s* ability to display and filter guide star catalog data is independent of APT. In *Aladin*, filters may be used to customize the display of catalog data. Filters not only allow you to change the symbol (e.g., shape, color, size) used to visualize a parameter; filters also enable you to set constraints, combine catalog parameters with arithmetic operators, and select objects based on combinations of parameters. Users can filter the guide star data using any of the guide star selection criteria discussed above. When assessing the availability of suitable guide stars, one may wish to select objects meeting the following criteria:

- Classified as stars;
- \(12.1 \leq J\text{ mag} \leq 18.6\);
- Not flagged as multiple object;
- Not flagged as variable object;
- Small GSC-II semi-major axis and eccentricity measures;
- Detected in more than one GSC-II pass band; and
- Detected on two or more GSC-II plates.

While applying a filter to your input catalog is not equivalent to the rules in the Guide Star Selection System, it will give proposers a more realistic idea of the availability of guide stars than the input catalog alone.
The Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) is continuing to perform well, but the Solar Blind Channel (SBC) is currently suspended. After an electronic upset in Hubble’s Science Instrument Control and Data Handling Unit (SI C&DH) in September 2010, we learned that we cannot turn off the high-voltage power supply of the SBC during such an event. Under certain circumstances, such a failure could result in damage to the Multi-Anode Micro-channel Array detector. Consequently, we have suspended all SBC observations until the installation of corrective updates to the flight software. We expect SBC science operations to resume towards the end of March 2011.

The ACS team has recently released two software items to mitigate the effects of charge transfer inefficiency (CTI) and the faint horizontal bias stripes seen in post-SM4 data. (See accompanying articles by J. Anderson and N. Grogin.) The software forms part of the Space Telescope Science Data Analysis System release in January 2011; downloads are also available from the ACS software web page at http://www.stsci.edu/hst/acs/software. The ACS team is working to incorporate the pixel-level CTI correction code in the ACS data-reduction pipeline, CALACS. We welcome any comments that users may have on these software tasks.

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References

Correcting Pixels for CTI in ACS’s WFC

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The harsh radiation environment of space takes a toll on charge-coupled-device (CCD) detectors. When cosmic rays (CRs)—high-energy protons, neutrons, and ions—impact CCDs, they frequently displace photoelectrons, causing the familiar trails in individual exposures. Particularly energetic events can even displace silicon atoms and create permanent defects in the silicon lattice. These defects cause two problems for astronomers. The first is that they can generate short-circuits within pixels, such that the pixels fill with charge even when there are no photons present. These are called “hot” or “warm” pixels (WPs). Defects in the silicon lattice can also temporarily trap photoelectrons while the detector is being read out. The result of this is charge-transfer inefficiency (CTI), which degrades the image quality. This article reports recent progress that has been made in correcting CTI in the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS).

During an exposure, photons impact the detector and generate electrons via the photoelectric effect. These electrons are collected within the pixel where they were created until it is time to read out the detector. The detector is read out by shuffling the charge cloud for each pixel down the columns to the serial readout register, then across this register to the readout amplifier, where the charge in each pixel is measured one pixel at a time. As a cloud of electrons is shuffled down the columns, it may encounter a defect in the silicon lattice, which can trap an electron temporarily. By the time the trap releases the electron, the original pixel cloud may have already been shuffled several pixels downstream. The result is that the electron gets released into another pixel, one located upstream from the original pixel. The recorded image of the source is thus smeared out in the direction away from the serial register (Figure 1).

The blurring caused by CTI presents serious problems for image analysis. If an astronomer measures a source’s flux by counting the photoelectrons within a certain photometric aperture—a small set of pixels on the CCD—he or she will not count the photoelectrons that were delayed and became associated with pixels outside the aperture. As a result, stars will be measured as fainter than they really are.

Over the years, the Institute has developed empirical corrections to account for these losses (see Cawley et al. 2001, Biretta et al. 2005, Riess & Mack 2004, Chiaberge et al. 2009). Unfortunately, these corrections depend sensitively on many factors, such as the size of the photometric aperture, the flux of the source, the date of observation, and the level of the background.

The delayed charge also causes problems for astrometry and shape-based types of image analysis, such as weak lensing (see Kozhurina-Platais et al. 2007). No empirical approach exists for correcting such measurements.

Another consequence of CTI is that CRs affect many more than the eight or so pixels they typically affect directly. While Drizzle is able to identify and remove the obvious CR blemishes, the CTI trails upstream of the CR often slip under the rejection threshold, resulting in a streaky background that becomes obvious in image stacks. This effect limits the sensitivity to faint structure (Figure 2).

Pixel-Based Corrections

Since empirical corrections are not available for anything more complicated than simple aperture photometry on a flat background (such as photometry on spatially variable backgrounds, or astrometric or shape measurements), many attempts have been made over the years to correct for CTI at the pixel level. The goal of pixel-level corrections is to estimate the most likely distribution of original pixel values that would result in the image that was observed, given the blur-inducing CTI in the readout process. To estimate the original pixel distribution, we must first simulate how CTI impacts the readout process at the pixel level. Then we must invert the process to solve for the original pixel distribution, which constitutes a mild deconvolution.

Early attempts at pixel-level correction had some aesthetic success, but did not achieve the photometric goal of restoring all the photoelectron counts to their native pixels. Furthermore, the procedures were prohibitively slow, sometimes taking days to correct a single exposure.
Recently, Massey et al. (2010) constructed a fast-readout model for the ACS/WFC detector by fitting exponential decay parameters, estimated in laboratory experiments, to the WPs in the science images of the Cosmos Evolution Survey. The researchers demonstrated clear success in removing the trails and cleaning up the images. Because the images had backgrounds of ~50 photoelectrons, they could calibrate their algorithm only for typical deep exposures, but not for shorter exposures with lower background. They also had no way to test the photometry to demonstrate that all the flux was preserved. Nevertheless, the clear success of their approach was a great encouragement to the ACS community.

Buoyed by their results, we decided to extend the Massey approach to address CTI at the lowest possible backgrounds (Anderson & Bedin 2010). Instead of studying the WPs in science images, we studied them in the multitude of dark images that the ACS/WFC takes as a regular part of its calibration program. In particular, we stacked the 168 dark exposures taken in September and October 2009 to generate a super-dark image, and analyzed the WP trails in it. In the left panel of Figure 3, we show a portion of the dark stack. There are so many warm pixels in the detector that their trails often overlap!

The schematic plot in the middle panel of Figure 3 shows how we characterized the WPs. Right: A plot showing the number of photoelectrons released as a function of distance from a very bright WP. The dashed red curve is a failed attempt to fit the profile with a dual exponential. Instead, our model uses a simple tabulation of the measured values (solid line).

Figure 3: Left: A portion of the stacked dark exposure with the parallel- and serial-readout directions indicated. Middle: A schematic showing how we characterized the WPs. Right: A plot showing the number of photoelectrons released as a function of distance from a very bright WP. The dashed red curve is a failed attempt to fit the profile with a dual exponential. Instead, our model uses a simple tabulation of the measured values (solid line).

portion of the dark stack. There are so many warm pixels in the detector that their trails often overlap!

The schematic plot in the middle panel of Figure 3 shows how we characterized the trail behind each WP: we simply tallied the number of photoelectrons in each pixel of the trail, normalized to the WP intensity. The right panel shows the average profile taken from over a hundred very bright WPs. The smooth profile shows that CTE-related charge trapping and release results in very simple trails. For example, the profile shown indicates that about 1% of the WP flux is assigned to the first upstream pixel. The trail can be detected a distance of 60 pixels, at which point about 4% of the WP intensity is represented across the length of the trail.

Laboratory experiments indicate two main species of traps. Nevertheless, when we attempt to fit this curve in Figure 3 with a dual exponential, we are not able to match both the ends and the middle. Rather than adopt an arbitrary number of exponentials in our readout-model, we chose to treat the trails empirically, as described below.

In addition to studying the bright WPs, we also studied faint ones. We found that when the WP intensity is lower, the total number of photoelectrons recorded in the trail is also lower, but the total in the trail goes down only as the square root of the WP intensity. This confirms the common wisdom that fainter WPs have a larger fraction of their electrons in their trails. The trail profile for fainter WPs is also slightly steeper.

We constructed a purely empirical model to describe the trails of WPs in the dark images based on the trapping and release probabilities. Although in reality, there are discrete charge traps within the detector, we have no way of measuring their locations and properties directly, so the model treats each pixel the same, assuming that each has the same probability of trapping a particular photoelectron (say, the first, tenth, or qth). By studying the WP trails, we parametrized this probability function with a simple curve and found that the probability of trapping the qth electron in a pixel varies roughly as q^{-1/2}, in general agreement with theoretical expectations (see Hardy & Dean 1998). The second aspect of the model relates to the trail profile, which tells us the probability that a particular trapped photoelectron will be
released into the moving cloud of electrons into the n-th upstream pixel. Our readout model keeps track of the state of the traps at all charge levels as the charge clouds are shuffled from upstream pixels to downstream pixels. The traps in each pixel fill and empty according to the parametrized probabilities. We adjusted the parameters of the model by hand to match the profiles behind the WPs in the darks under the assumption that WPs were initially single-pixel events.

The final step is to invert the process to estimate the original distribution of pixel counts that could have been read out as the observed blurred image. We perform this step by iteration, first assuming the source image was the observed image, then tweaking the source image until the output image resembled the observation. Since CTI has a small fractional impact on the image, convergence is rapid. It generally takes about 10 minutes on a 3 GHz machine to correct a single 4096 × 4096 ACS/WFC science image.

After optimizing the new algorithm on WPs in the super-dark frames, we applied it to real-world science images. Figure 4 shows the algorithm in operation for the same short exposure of 47 Tucanae in Figure 1. A clear qualitative success!

![Figure 4: Left: a close-up of a short exposure of the outer field of 47 Tucanae before correction. Right: the same image after CTI correction.](image)

To show that the flux was quantitatively restored, we analyzed the standard, vertically dithered data-sets that are designed to highlight CTI and found that stars are indeed recovered with the same flux at any position on the detector. The difference we found between pre- and post-correction photometry is similar to the most recent empirical corrections given in Chiaberge et al. (2009). This is a nice confirmation that in the domain where the empirical photometric corrections are valid, both approaches yield similar corrections. We also showed that the algorithm for pixel-level correction removes the signature of CTI for astrometry and shape measurements as well.

**Future Improvement**

The only downside of the pixel-level correction is the amplification of noise. Although unavoidable in any deconvolution, noise amplification is worse in this application because the observed image has both read noise and Poisson statistical noise. The Poisson noise went through the blur-inducing readout process, so it is appropriate for the algorithm to correct it. The read noise, however, was generated after the photoelectron clouds had been shuffled through the pixels, so it did not take part in the CTI blurring. As a consequence, de-blurring the image amplifies the read noise inappropriately. There is no way of knowing what portion of pixel-to-pixel variation is due to source structure or to Poisson or read noise. Nevertheless, it is possible to conservatively estimate the maximal impact of read noise on the image and perform the CTI correction only on the remainder. We are currently exploring how best to do this.

The code that does the pixel-level correction for CTI blurring has been translated into Python and has recently been released as a PyRAF task. It is currently available on the ACS homepage, so that interested users can have immediate access to the correction for their ACS/WFC science programs. The code currently assumes that CTI losses have increased linearly over time since Servicing Mission 3B. We are studying the darks month-by-month since installation in 2002 to determine the best way to parametrize the CTI time dependence.

The “dark” images used in the initial study could not probe the lowest background levels. The exposure times were about 1000s, and the WPs producing more than 15 electrons were so numerous that it was impossible to measure their trails in isolation. To remedy this, in CAL/ACS-12327, the ACS team has taken a set of dark exposures with 33s, 100s, and 339s. This data set will allow us to better study the behavior of the small electron packets at low background levels. Because many short science
exposures have backgrounds below 5 electrons, it will be important to extend our characterization of CTI trails to this low-background regime.

CTI losses occur at the detector level, so it is not ideal to perform the correction on _flt images, which have had been corrected for dark current and flat fields. The ultimate plan is to incorporate a pixel-level correction into the CALACS pipeline after bias subtraction but before the other processing stages. We are studying how this plan will impact, for example, dark construction and dark subtraction, with an aim to implement the correction within the pipeline in late 2011 or early 2012.

We hope that a similar pixel-level approach will work for all Hubble CCDs. Over the coming year, we will estimate the model parameters for Wide Field Camera 3, Space Telescope Imaging Spectrograph, the ACS High Resolution Channel, and Wide Field Planetary Camera 2. CTI losses in WFC3 images are already noticeable, so this effort is particularly timely. For WFC3, additional CTI mitigation is possible by using charge injection, which is a low-noise way of pre-flashing an entire image or specific rows in an image. These routes are being explored in parallel.

References
A Touch of Zebra in the Old Workhorse: Correcting the Bias Striping in Post-SM4 ACS Images

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Hubble's Advanced Camera for Surveys (ACS) includes a Wide Field Channel (WFC), the telescope's workhorse for visible-light pictures from 2002 until its electrical failure in 2007. The WFC has resumed this role following Hubble's Servicing Mission 4 (SM4) in 2009, thanks in part to replacement electronics for controlling its charge-coupled device (CCD) light-detectors. These replacement electronics have brought the WFC back to life as an even more sensitive instrument for detecting faint light from the cosmos. This is because the electrical noise contribution to each pixel in an image, the so-called "read noise," is now 20% less than the WFC had with its original CCD electronics. However, the new electronics also contribute a low-level noise that appears as a fluctuating horizontal striping across all post-SM4 WFC images—a touch of zebra in the old workhorse (Figure 1, top).

Specifically, this striping noise arises from the application-specific integrated circuit (ASIC) that provides bias and reference voltages for the two WFC CCDs. M. Loose described the characteristics of this ASIC in the proceedings of the 2010 HST Calibration Workshop (http://www.stsci.edu/institute/conference/cal10/proceedings). One of the ASIC reference voltages exhibits a low-frequency flickering (1mHz to 1Hz) that is not nulled-out during the CCD read, and therefore it appears as an additional time-variable contribution to the image bias.

The restored WFC no longer has a completely steady bias. The time variation of the signal is consistent with electronic "1/f" noise, also known as "pink noise"—meaning the flickering is more pronounced over longer time-scales or lower frequencies. The implication for WFC images is that the variation is too slight to perceive along an image row, but the bias level does noticeably vary from row to row, and more strongly between more distantly separated rows. Moreover, the bias striping appears to be uniform among all four of the amplifiers used to read the two WFC CCDs: the same striping pattern appears across the amplifier boundary of a given WFC CCD, and is mirror-reflected across the WFC CCD gap. This bias variation amounts to less than one-quarter of an individual pixel's read noise. Nevertheless, the striping appears prominently in low-background WFC images because human vision is so attuned to pattern recognition.

In quantitative terms, the standard deviation of the bias striping is 0.9 electrons (Figure 2), as compared with the WFC read noise of >4 electrons. After a year of monitoring this post-SM4 effect, we find the noise is steady within a couple percent from month to month. We also find that striping between images is largely uncorrelated, because averaging together 4 bias images diminishes the striping approximately as the square root of N. Because of this dampening, the post-SM4 WFC biweekly super-bias calibration images show overall noise comparable to pre-2007 levels without the need for frame-by-frame stripe removal.

The limited WFC overscan regions—columns along the image edge that are insensitive to light and record only the bias level—cannot track the low-level striping with sufficient precision. We are therefore compelled to estimate the stripe level from the science region. This complicates stripe removal from individual non-bias frames such as science exposures and calibration dark frames. Along with the bias stripes, there is a risk of mistakenly removing image structure along the vertical axis in a science (or dark) exposure. A WFC super-dark calibration image, averaging together some 24 individual dark exposures, is effectively stripe-free. However, ACS WFC science programs rarely comprise so many frames to average the striping noise away.

The ACS team tested various codes for removing bias stripes from science images. Each code performed row-by-row correction using a different algorithm for modeling the stripes in the presence of increasingly complex astronomical scenes. Our test suite comprised four pre-failure WFC programs spanning a broad range in sky level and scene complexity. These included the large galaxy NGC 1300, the crowded stellar field 47 Tucanae, and long-exposure, blank-field images with wide- and narrow-band filters. We seeded the pre-failure images with the same stripes to estimate the noise and evaluate the algorithms.

Figure 1: (top) A bias image for one of the two CCDs of the ACS WFC, with super bias subtracted to highlight the horizontal striping seen in post-SM4 images. (bottom) Same image, after application of stripe-removal software. The remaining read noise in the lower image is more than four times larger than the corrected striping, but the eye easily picks out the striping noise because it is highly correlated across the rows.

From Bias to Super Bias
For readers not versed in the jargon of digital photography, a brief discussion of a CCD's "bias" is in order. During an exposure, the CCD keeps track of the light falling onto it by converting that light into miniscule packets of electric charge. At the end of the exposure, the accumulated charge at any given pixel of the CCD is a surplus voltage, which is digitized into a number of counts. This digitization is an imperfect process—subject to "read noise," for example. Digital converters behave badly in various ways if the surplus voltage is measured from zero. Because of this, the surplus voltage from captured light is measured not as an offset from zero, but as an offset from a fixed voltage—the bias. Thus even a zero-second CCD exposure, known as a "bias image," is read out with a comfortably positive number of counts—over 2000 counts in the case of the ACS WFC. Taking many bias images repeatedly measures the bias counts, achieving a "super-bias" image that overcomes the read noise. The very first stage of processing a CCD image for science is to subtract this noise-free super-bias image.
with dozens of independent realizations of the striping noise, as measured from post-SM4 bias frames.

We rated performance of stripe mitigation by comparing the standard deviations of the residual (imperfectly corrected) striping for each algorithm. The best results were achieved for the narrow- and wide-band blank-field images, where the injected striping noise was reduced to 0.3 and 0.4 electrons (e−), respectively. The CCD-spanning large-galaxy case had uneven results, worsening the scatter to 2 e− in half the trials. All the codes failed badly for the crowded stellar field 47 Tuc, often worsening the scatter to much greater than 10 e−. We have posted on our website the instructions for using the code—a stand-alone Python script—that performs best overall for stripe removal (http://www.stsci.edu/hst/acs/software/destripe/). We have also contributed this code to the Space Telescope Science Data Analysis System software suite for PyRAF, with the task ACS DESTRIP in the package acstools. Due to the instances of poor performance, however, we have not yet incorporated de-striping into the automated ACS calibration pipeline (CALACS).

In the case of science programs where low-level, row-correlated noise may be a severe systematic contamination, such as weak-lensing or faint-isophotal analyses, we strongly recommend the use of this Institute-tested de-striping algorithm. It may also be useful for cosmetic improvement of image mosaics, as can be seen for the large galaxy NGC 6217 observed in the Hα filter (Figure 3), which was the post-SM4 first-light target. Although the eye easily picks out the row-correlated striping in these ACS WFC images, we emphasize that the standard deviation of this striping noise is less than 25% of the WFC read noise. Our post-SM4 observations of WFC photometric calibration fields show no measurable impact upon aperture photometry of compact sources with local-background estimation.

**Figure 2:** The distribution of intensities for ACS WFC bias stripes, as measured from the first year of bias frames taken post-SM4. The standard deviation of this distribution is about 0.9 e−, less than one-quarter of the WFC read noise. Except for the tail to the left, the shape of this distribution is close to Gaussian (red dashed line), and the best-fit Gaussian standard deviation, about 0.74 e−, has been highly stable since SM4.

**Figure 3:** The ACS WFC bias striping (right half) and its correction (left half) for a mosaic image of the galaxy NGC 6217 using the Hα filter. The low background of this narrow-band image accentuates the striping. The correction software performs well for this case, where a galaxy fills half of a WFC CCD.
Those of us who are committed spectroscopists know the unparalleled value of a spectrum. The results of the Cycle 18 proposal selection process affirmed that many *Hubble Space Telescope* users feel similarly: in Cycle 18, orbits with the Cosmic Origins Spectrograph (COS) account for 23% of GO prime orbits allocated. The overwhelming majority of these orbits use COS far-ultraviolet (FUV) spectroscopic configurations. COS/FUV spectroscopy also accounts for about 29% of Snapshot (SNAP) orbits.

The decline in sensitivity of the COS FUV spectroscopic configurations continues, but the behavior has changed. Discovered midway through Cycle 17, the phenomenon was described in the instrument science report (ISR), COS 2010-15, “Early Results from the COS Spectroscopic Sensitivity Monitoring Programs,” by Osten et al. ([http://www.stsci.edu/hst/cos/documents/isrs/ISR2010_15(v1).pdf](http://www.stsci.edu/hst/cos/documents/isrs/ISR2010_15(v1).pdf)).

The monitoring program uses repeated observations of spectrophotometric white-dwarf standard stars to measure any time dependence to the spectroscopic sensitivity. The main finding in the ISR for the FUV detectors was that the decline increased for longer wavelengths, down by about 4–6% per year at short wavelengths and by 12% per year at the longest wavelengths. Observations taken since mid March 2010 have exhibited a flattening of the slope at the longest wavelengths. As a result, the FUV data are now consistent with a value almost independent of wavelength: a weighted mean of $-5.1 \pm 0.2\%$/year (see Figure 1). This result suggests that the sensitivity decline of the FUV detector has two origins: one is producing a more or less constant level of sensitivity decline, and another—now past—causing the initial decrease. The updated time-dependent sensitivity reference file reflects this new information, with a change in the FUV slope occurring on the date 2010.2.

The COS team at the Institute is setting up routine monitors of the data quality, enabling automated checking of the instrument’s performance. Examples include monitoring the accuracy of acquisitions; automated monitoring of the dark current on both the FUV and near-ultraviolet (NUV) detectors; routine searches for short time-scale, high-voltage transients; weekly images of the accumulated photons falling on the detector; and monitoring the decline in the brightness of the lamp. The results of these monitors will be available from the main COS web pages.

The aim of the Cycle 18 calibration program for COS is to maximize the scientific performance of the instrument. Nevertheless, with four science instruments now operating on *Hubble*, there is a need to minimize internal and external calibration orbits. The team took a critical look at routine monitoring programs established in Cycle 17 and cut back on programs where previous monitoring revealed stable behavior, or where configuration usage in Cycle 18 was dramatically lower than in Cycle 17. In these cases, we judged that we could afford reduced monitoring frequencies. Continued regular monitoring includes measurements of the NUV Multi-Anode Micro-channel Array fold distribution, detector dark rates, spectroscopic sensitivity, and internal/external wavelength scales.

We continue a special program designed to characterize geocoronal Lyman-alpha airglow in blank fields for users interested in modeling this effect in their data. A new program aims to improve the accuracy of FUV sensitivity characterization to better than the 5% now possible. A companion calibration program for the Space Telescope Imaging Spectrograph will investigate the use of a particular DB white-dwarf for flux calibrations in the COS/G130M mode. Unlike the DA white dwarfs that are typically used, DB white dwarfs do not have strong photospheric Lyman alpha absorption lines and their flatter spectral energy distributions provide a more uniform signal-to-noise ratio across the COS UV detectors. The object under consideration, WD0308-566, could be used for flat-field monitoring or additional flux calibrations with an enormous savings in time compared with the standards currently in use. The STIS observations will ensure that the target can be modeled sufficiently accurately (<1%) to serve as a flux calibrator.

In time-tag mode, the FUV detector records the pulse-height amplitude (PHA), in addition to the time and location of each detected photon. The PHA gives a measure of the gain of the detector, which means the number of collected electrons after one photon strikes the detector at a given position. The COS team has determined that the peak of the PHA distribution has been steadily shifting to smaller gain

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*Figure 1: The sensitivity trends of the COS FUV detector since mid March 2010. Symbols indicate grating and segment. With the exception of G140L/segment B, all data are consistent with a nearly wavelength-independent sensitivity decline of 4–6% per year. The scatter in the data does not show any trends with detector segment or grating, in contrast to the results from early in Cycle 17.*
values (see Figure 2). This “gain sag” is most apparent in regions of the detector subject to the largest photon accumulations. On FUV detector segment B, these regions are where geocoronal Lyman-alpha emission from the most used aperture (the Primary Science Aperture) and central wavelengths of grating G130M are located. Since the data are filtered by PHA, events falling below the current threshold of PHA = 4 are removed from the events that contribute to extracted spectra. Several artifacts due to gain sag—“absorption features”—are now apparent in science data. In late December the team delivered a new reference file which has a reduced PHA lower threshold of PHA = 2. Application of this new reference file to data will remove the absorption features. It additionally raises the dark count rate by 7% compared with the PHA = 4 threshold, although the dark rate is still low, between 3 and 4 x 10^{-6} counts/sec/pixel.

There is no relation between the COS gain sag and the time-dependent decline in spectroscopic sensitivity. Although a reduction in the number of photoelectrons produced by a photon occurs, if the gain is high enough the probability of detecting the photon is not affected. The testing of short-term strategies includes marking the low-gain regions with data quality flags and performing position-dependent pulse height filtering. The COS team is investigating long-term options, including raising the voltage back to its original value or moving to a new position on the detector.

Results from early in the COS on-orbit validation revealed that the instrument has sensitivity below 1150 Å (McCanless et al. 2010, ApJ, 709, L183). Two supplemental calibration programs executed in Cycle 17 explored this wavelength region further. One program utilized two new central wavelengths of the G130M grating (G130M/1096 and G130M/1055) to obtain higher spectral resolution and sensitivity in this region, compared to the G140L grating. Figure 3 compares the effective areas. The spectral resolution of the new G130M central wavelength settings is greater than about 2000 (=\lambda/\Delta\lambda) below

Figure 2: The evolution of the gain versus x position on the COS FUV detector at a variety of times since COS was installed on Hubble. The “modal gain” is the peak of the pulse height distribution for events in the spectral extraction region. The large jump between the top (green) curve and the lower (blue) curve is the result of a lowering of the high voltage of the FUV detector on August 15, 2010. Since then the gain has been steadily decreasing, and pulse-height minima are appearing at regions of enhanced geocoronal Lyman-alpha emission. In the most affected regions, standard screening through CAL/COS produces “absorption features,” when valid photon conversions produce pulse heights of photoelectrons that fall below the threshold.
1050 Å, and also exceeds the spectral resolution of the G140L/1280 setting, by up to a factor of two in this wavelength range. The new central wavelengths allow users to exploit this wavelength region, while avoiding the large increase in effective area at longer wavelengths. This increase is a factor of roughly 30 in effective area, and may cause a local rate violation above 1150 Å, depending on the spectral energy distribution of the source. These new modes will be available for Cycle 19 proposers.

Another calibration program will improve the flux calibration of the G140L/1280 configuration to 3% in the 900–1150 Å region and explore the sensitivity below 900 Å.

STIS Update

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Parallel and Serial CTI of the STIS CCD

After 13 years on orbit, the Space Telescope Imaging Spectrograph (STIS) Charge-Coupled Device (CCD) detector shows the effects of accumulated radiation damage. In particular, its charge transfer efficiency (CTE)—a measure of the ability of the CCD to move charge from one pixel to the next during readout—continues to degrade. CTE is expressed as the fraction of charge successfully transferred. In practice, one usually refers to the charge transfer inefficiency (CTI), where CTI = 1 – CTE. The CTI in both the parallel and serial directions on the CCD is measured twice per year. The most recent measurements, plotted in Figure 1 (on next page), were derived using the extended pixel edge response test of Goudfrooij et al. 2009 (STIS ISR 2009-02; http://www.stsci.edu/hst/stis/documents/isrs/200902.pdf).

An interesting pattern is apparent in Figure 1. While the CTI in the parallel direction (upper panel) has remained roughly constant since the last servicing mission (SM4), the CTI in the serial direction (lower panel) has risen steeply. The scatter in the upper plot illustrates the temperature dependence of the parallel CTI. The serial CTI, however, appears to be independent of temperature. The parallel CTI remains an order of magnitude larger than the serial CTI. We will continue to monitor both effects.

Recent Trending of the STIS NUV MAMA Dark Rate

Both the near- and far-ultraviolet (NUV and FUV) Multi-Anode Microchannel Array (MAMA) detectors were disabled in mid-September 2010 while a change to the flight software was developed. The purpose of the change was to protect the detectors in the event of an electronic upset in the science-instrument command and data-handling unit. The software update was installed on 15 November 2010 and appears to be working properly. The dark rate in the NUV MAMA detector has fallen steadily since the repair of STIS during SM4, reaching a mean of about 0.0035 counts/sec/pixel (at a temperature of 38° C) in August 2010. The dark rate rose during the two-month shutdown of the MAMA detectors, but it has since fallen to about 0.004 counts/sec/pixel (in early December 2010) and continues to decline.
Wide Field Camera 3 Update

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Wide Field Camera 3 (WFC3) continues to function well. It has nearly completed its Cycle 17 science and calibration programs, and is now well into Cycle 18. This article highlights some of the accomplishments and future directions of the WFC3 calibration program, which has evolved through three stages.

Following installation, the initial calibration effort was designed to characterize the instrument and verify that its performance met the expectations from pre-flight calibration. The second stage, the Cycle 17 program, established the working calibrations and explored the long-term stability of the instrument. The third, the smaller Cycle 18 program is extending the calibrations, continuing to monitor stability, and opening up new parameter space.

Photometric Calibration

Following its May 2009 installation in Hubble, WFC3’s performance has met or exceeded our expectation. The system throughput is 5–15% greater than indicated by ground calibration. Careful monitoring of standard stars through a broad set of filters shows that the throughput is very stable (<0.3% variation in the ultraviolet-visible [UVIS] and <0.5% in the infrared [IR]). WFC3 is now well calibrated on the primary Hubble standard stars.
Astrometric Calibration

Given the wide use of MULTIDRIZZLE software to combine exposures in the same filter—even taken with two or more different instruments—we have made a significant effort in Cycle 17 to obtain a stable astrometric calibration for WFC3. Astrometry with WFC3 was calibrated in ten UVIS and five IR filters to an accuracy of 0.1 pixel, and the solution for the geometric distortion was solid to better than 0.05 pixels. Nevertheless, combining images between visits (or instruments) still requires significant manual intervention, because the astrometry of the guide stars is considerably less precise. Also, the line-of-sight stability of WFC3 relative to a Fine Guidance Sensor is about 0.35 UVIS pixels or 0.31 IR pixels over a two-orbit visit.

Dark Frames

The WFC3 dark-frame calibration was straightforward in both the UVIS and IR channels. As expected, the monthly annealing of the CCD detectors successfully removes the majority of new warm pixels. Calibrations of the warm and hot pixel population are maintained on four-day centers, and are available from the Institute (http://www.stsci.edu/hst/observatory/cdbs/SIfi Info/WFC3/reftablequeryindex). The IR detector appears to be quite stable in the radiation environment of space.

We have added to the list of “bad” pixels some optical features on the mechanized mirror that selects the channel (and is closed during focus operations). We have aggressively masked poorly behaved pixels, particularly those with occasionally anomalous dark current. Users should consider which “bad” pixel features to exclude from their observations based upon both the number of dithered exposures available and their particular science goals.

Flat Frames

The low-spatial-frequency flat fields (L-Flats) have proven time-consuming to calibrate. During ground calibration, we obtained both internal and external flat fields. The internal ones provide reasonable high-spatial-frequency flats (pixel-to-pixel or P-Flats), but have significant limitations regarding illumination. Their primary utility is to verify the stability of the P-Flat obtained from the external, ground-illumination system. This calibration appears very stable in all filters in both channels. The mismatch in the large-scale illumination pattern, however, results in 4–5% peak-to-peak errors in the flat fields at low spatial frequencies.

The high level of residual L-Flat error was expected. We made a major effort in Cycle 17 to obtain good L-Flats via repeatedly stepped exposures of the globular cluster Omega Cen (which also supported the astrometric calibration). The analysis of these data is subject to significant systematic errors, driven in part by source crowding and variations in the point-spread function (PSF) due to telescope breathing.

For the IR channel, the combination of ~2000 long-exposure, broad-band images contains sufficient background flux to create a high-quality L-Flat. These data demonstrated both that the systematics in the cluster-based flats are understood and that the low-spatial-frequency errors in the ground calibrations are mostly independent of wavelength. Based on these results, we corrected all IR ground flats using the smoothed background-light L-Flats. This calibration provides the confidence needed to proceed with the L-flats derived for the star cluster for the UVIS channel, and we will release the results shortly.

We are exploring the potential value of flat fields obtained using the Moon-lit Earth as an illumination source, to validate and possibly improve the flat fields. Early experiments look promising. (The sunlit Earth is too bright for broad filters in either channel, and short exposures produce streaks.)

Charge Transfer Inefficiency in the WFC3 UVIS Channel

In an unexpected and unhappy development, the Charge Transfer Inefficiency (CTI) of the WFC3 UVIS channel CCD detectors is increasing faster than we found for the ACS CCDs in their first year in space. Ground-based testing prior to Servicing Mission 4 indicated that the WFC3 CCDs had essentially the same susceptibility to radiation damage as the ACS CCDs. However, the observed rate of increase in CTI is ~2.5 times that of ACS in 2002–2003. The explanation appears to be timing—that WFC3 was placed in space during the solar minimum, when the charged-particle environment, mainly the South Atlantic Anomaly, is at a maximum. ACS is also experiencing an acceleration of CTI since SM4.

In response to increasing CTI, we tested the Charge Injection mode (CI) for WFC3 early in Cycle 18. Despite mixed results during ground testing, the in-flight data indicate near complete correction of CTI. The CI mode injects ~13,000 electrons into every \(N^{th}\) row, where \(N\) is set to 10 or 17). Those rows have higher effective read noise (~15–20 electrons), but the rows in between have only slightly increased (~1 electron greater) read noise. The ACS team is in the process of developing a post-observation algorithm to correct for the impact of their (much more severe) increase in CTI. At this time, Cycle 19 WFC3 observers can expect to have both CI and the post-observation algorithm available as options to reduce the CTI of their images.
Charge Persistence in the WFC3 IR Channel

A well known and widespread characteristic of mercury-cadmium-telluride IR detectors is the persistent charge following observations of bright targets. In the low-background environment of WFC3, the IR detector shows significant persistence, for several hours following exposure, to sources that approach full well. This effect was known prior to launch, and observers are required to obtain dithered observations to reduce the impact on their observations.

The Institute has examined the Cycle 17 and Cycle 18 proposal pools to identify targets that will produce large numbers of pixels with high levels of persistence. Wherever possible, other WFC3/IR observations are not scheduled following such exposures.

Using additional characterizations of the persistence behavior, we have built a model that can both identify and—with lesser accuracy—calibrate the pixels in each observation that are expected to have additional dark current due to persistence. These mitigating steps will be useful to individual observers to correct all affected observations in their visit. During Cycle 18, we are experimenting with these algorithms and working to create a prototype pipeline to generate calibrations for each observation.

High-Contrast Observations

One question that has arisen in several contexts is how well WFC3 performs in high-contrast observations. Such performance was not a design goal for WFC3, nor was it characterized in ground testing or early in-flight calibrations, as the High Resolution Channel of ACS and the Near Infrared Camera and Multi-Object Spectrometer were expected to support coronagraphic observations. Nevertheless, early in Cycle 18 we performed a high-contrast experiment to determine the WFC3’s ability to measure faint sources within the extended point-spread function of a bright point source. Watch for WFC3 ISRs on this topic in early 2011.

Slit-less Spectroscopy

Cycle 18 saw a considerable increase in the usage of the IR slit-less spectroscopic mode of WFC3. In recognition of this, the Institute hosted a workshop 15–16 November 2010, to discuss the reduction and calibration of these data. This workshop also marked the handover of responsibility to STScI for these calibrations and user support from our colleagues at the European Space Agency’s Space Telescope European Coordinating Facility. For the past decade, they have supported the development of calibration software, ground testing, in-flight calibration, documentation, and user support for all aspects of spectroscopy with WFC3. We extend our thanks and appreciation for a job very well done.

Further Information

Far more detail is available on the calibration status of WFC3 in the recently released Cycle 19 version of the WFC3 Instrument Handbook, the recently updated WFC3 Data Handbook, and in numerous Instrument Science Reports available at www.stsci.edu/hst/wfc3.
PYETC: A New Exposure Time Calculator for Hubble

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The Institute has recently developed a new exposure time calculator (ETC)—PYETC, a web-based application that calculates either the exposure time needed to achieve a certain signal-to-noise ratio (SNR), or the SNR that would be achieved by a certain exposure time. Users need such calculations to explore the parameter spaces of instruments and detectors, to prepare realistic proposals, and to plan optimal observations following proposal selection.

Achieving the 10% accuracy goal of PYETC requires good models of many types of astronomical targets and environments. It also demands accurate, up-to-date information about the telescope and instruments. To achieve this, the instrument teams at the Institute monitor the observatory closely, constantly gather new calibration data, and improve the fidelity of the calibrations. The new system’s design allows quick changes to the computational engine and instrument data. It supports many instruments with common code. In operation, it balances loads and handles failure and handover to backup systems during times of heavy usage. This robust design and ongoing maintenance ensures that the ETC promptly makes any significant variation in the response of an instrument available to users.

PYETC features

PYETC has the capability to support multiple ETC versions on the same computer, and provides one-step installation. These features provide the ability to make changes, validate them, and provide them to users in short order.

PYETC offers a simpler codebase, which can be adapted to other instruments and missions, like Webb, for example. Although previous versions of the ETC were technically capable of such adaptation, they demanded significant resources to make the necessary changes. The new tool makes it easy.

PYETC makes testing easier and more effective. Verifying the accuracy and correctness of any changes to a Hubble ETC can be daunting, due to the large number of input parameters and observing modes. PYETC uses a test interface with a consistent test scheme. Also, PYETC expands test coverage to a wider
PYETC separates computational and web functionality. All ETC calculations are contained within one part of the system, while the web framework (which uses Django) processes the information to and from the user. In the future, this separation will allow users with only a personal computer to run PYETC calculations using PYTHON scripting, and to write PYTHON scripts that directly use the calculation engine, for both batch processing and science exploration.

The instrumental information and other data used by PYETC to perform its calculations are, unlike older versions, independent of the software. These data are now stored in the calibration database system (CDBS), which will be accessible to the instrument teams for updating, validating, and testing. It will also be available to users who want to know the details of their calculations, or who wish to run batch PYETC calculations. Furthermore, following CDBS standards, these files will be under version control and strict protocols to ensure the quality of the data.

PYETC, like previous ETC versions, uses the PYTHON version of SYNPHOT—PYSYNPHOT—which is an improved implementation of the synphot package in STSDAS. Like the old package, PYSYNPHOT simulates the photometry of the selected source by computing the detected photons as a function of wavelength (and for spectrographs, per detector bin) for a specified input spectrum, and for the known values of throughput and detector quantum efficiency.

The look and feel of PYETC for Cycle 19 is the same as previous ETC versions. Nevertheless, users with previous experience will notice many improvements, such as explicit wavelength ranges for spectroscopic gratings (Figure 1), and consistency in the arrangement of input and output forms. The output forms offer additional information that may be useful for planning observations or entering source parameters for the calculation (Figure 2). They also provide the ability to produce plots and tables of the results of simulated observations.

Plots of the input spectrum and the throughput are available for all modes. For spectroscopic modes, this includes plots of the SNR and total counts from each contribution as a function of wavelength. The new ETC allows the user to scale the plots or zoom the data along the X or Y axis.

The first version release of PYETC (ETC 19.1) was concurrent with the call for Cycle 19 Phase I proposals. We plan to release a second version (ETC 19.2) for Phase II around May 2011, with the announcement of the selected proposals. This version will provide the same functionality as the previous one, but will include improvements and fixes to problems. It may also support some instrument modes not included in the first release. As always, users will find information related to the changes from the prior version in the ETC release notices.

In summary, PYETC, the new ETC, is a more robust and flexible tool, which is reliable and easier to change. It adds to the functionality of the previous ETC, and reduces maintenance time and effort. It also eliminates many deficiencies found with the previous ETC versions.
Multimission Archive at
STScI

Alberto Conti, aconti@stsci.edu, for the MAST Team

The Multimission Archive at STScI (MAST) is the NASA repository for ultraviolet and optical observations from both active and legacy missions. MAST supports the astronomical community by maintaining public-access interfaces to its collections, and providing expert user support and access calibration and analysis software.

As of November 2010, the volume of MAST’s data holdings was 155 terabytes (TB). Approximately 72% of this volume is data from Hubble Space Telescope, including reprocessed data in the Hubble Legacy Archive (HLA); 16% is from Galaxy Evolution Explorer (GALEX); 10% is high-level science products (HLSPs) or data from Far Ultraviolet Spectroscopic Explorer, X-ray Multi-Mirror Mission–Newton, or the Digitized Sky Survey; and 2% is from Kepler.

MAST User Group

On July 16, 2010, the MAST User Group (MUG) held its annual meeting at the Institute. The MUG provides an essential user perspective on archive operations and development, including assessments of the priorities for short- and long-term operational and scientific enhancements to MAST. The 2010 MUG report and the presentations made at the meeting by MAST staff members are available at http://archive.stsci.edu/mug/index.html.

Figure 1: MAST standard interface to the Kepler-GALEX cross-match database. This interface does not require knowledge of SQL, rather it uses a form-based page to allow users to search for objects of interest.
Visit-level or Multi-visit?

Visit-level combined images are distinguished from the multi-visit deep images (known as Level 3), which combine observations taken in independent Hubble visits with independent guide star acquisitions. Level 3 data may be either deeper (though stacking observations at roughly the same pointing) or wider field (though combining observations at different pointings). There is a more detailed description of visit-level data on the HLA “Getting Started” page (http://hla.stsci.edu/hla_help.html).

The New Kepler-to-GALEX Cross-Match Tool

Coinciding with Kepler’s Cycle 3 guest-observer (GO) season, MAST is happy to announce the availability of a cross-match tool between GALEX sources and the Kepler initial catalog. Its purpose is to extend the wavelength baseline from the optical magnitudes of Kepler ground support (Sloan-like g, r, i, and z filters) to near- and far-ultraviolet bandpasses. This extension is especially important for selecting hot star targets when only photometric data are available.

The cross-match tool is available two ways: by an interface form (https://archive.stsci.edu/kepler/kgmatch/search.php) and by Structured Query Language (SQL) queries in the C SJOBS tool environment (http://mastweb.stsci.edu/kplr/casjobs/).

The form has the look and feel of other MAST mission-data retrieval forms (Figure 1). It works for simple queries that yield a relatively small list of results (<15,000 rows). Users of the form need not know the SQL query language, which is an advantage.

Originally, the Department of Physics & Astronomy at the Johns Hopkins University developed C SJOBS for large, batch queries in SQL. MAST adapted C SJOBS—which is useful for sophisticated database queries, and requires knowledge of the SQL query language—for the GALEX and Kepler missions. A help page devoted to Kepler GO proposers is also provided. C SJOBS remains the recommended way to access the Kepler database for users interested in storing the result of their queries on MAST databases, and for group collaborations. C SJOBS is a powerful tool, allowing nuanced and complicated queries when necessary.

The cross-match tool allows easy access to accurate and complete databases of objects observed by both Kepler and GALEX. Here, “accurate” refers to the performance of our table of one-to-one matches within a search radius of 2.5 arcsec of the position of a Kepler object, and “complete” means we include other possible GALEX matches within a search radius of 5 arcsecs. This approach reflects the fact that an automated cross-match algorithm cannot always unambiguously select the correct match between objects observed by different missions. At times, the best match for an object observed by one mission with objects observed by another mission is not the best match in the reverse direction.

Both the form and C SJOBS implementations support uploads of target lists.

In the near future, MAST will provide a complementary tool on its GALEX/C SJOBS site to facilitate GALEX-to-Kepler cross-matches.

GALEX General Release 6 All Sky Survey Data

All data for General Release 6 (GR6) of the GALEX All-Sky Imaging Survey (AIS) has been delivered to MAST. The data are available on the MAST/GALEX web site (http://galex.stsci.edu/GR6/). A description of the most notable changes between GR6 and the old GR4/5 can be found at http://galex.stsci.edu/doc/gr6_cs.txt. A delivery of GR6 grism data products, expected in January 2011, will complete the GR6 data delivery. The grism data will be available on the News corner and on the table of survey tiles, both located on the MAST/GALEX home page (http://galex.stsci.edu).

Availability of New High-Value Sky Regions Observed by GALEX

The operations phase of the GALEX mission is now scheduled to end on September 30, 2012. In the intervening time, GALEX has begun to observe sky regions of high science value that have not yet been well observed—or in some cases not observed at all. Starting in November 2010, the GALEX project began delivering the data to MAST in monthly installments which will be made publicly available immediately upon ingest. These deliveries are called “secondary MIS” datasets (Medium Imaging Survey), and can be found within the MIS survey area of the MAST/GALEX web site. First notice of availability will appear on the News corner of the home page. This notice will contain a link to a list of secondary MIS tiles, which will grow over the duration of this observing program.

The Hubble Legacy Archive

The Hubble Legacy Archive (HLA; http://hla.stsci.edu) provides enhanced data products for many Hubble instruments, as well as an integrated search, quick-look, and retrieval interface for all Hubble data. As of Data Release 4 (March 2010), the HLA includes visit-level combined data (VLCD) for all
science observations with imaging instruments—Advanced Camera for Surveys (ACS), Wide Field Planetary Camera 2 (WFPC2), and Near Infrared Camera and Multi-Object Spectrometer (NICMOS)—that were publicly available through February 2010.1

Users can identify data of interest by location, target name, instrument, exposure time, and a variety of other selection criteria. A graphical search interface has the ability to display the footprints of each data product. Users can view and retrieve public data through the HLA interface. For proprietary data, a convenient link is provided to the MAST retrieval form. Several movie tutorials are available (http://hla.stsci.edu/hla_movie.html) to help new users understand the capabilities of the HLA interface.

The HLA provides three categories of advanced products: source lists, mosaics, and HLSPs. Source lists for VLCD from ACS and WFPC2 were obtained using DAOPHOT and SOURCE EXTRACTOR. In both cases, sources are identified in a combined image using all available filters, which allows easy cross-identification of sources across filters. DAOPHOT source lists are recommended for point sources, while SOURCE EXTRACTOR lists are preferred for extended sources.

Mosaics (http://hla.stsci.edu/hla_faq.html#Mosaics1) increase depth and sky coverage by combining data from multiple visits to cover contiguous areas of the sky. Mosaics based on ACS images are currently available for 67 pointings, for a total of 143 single-filter images. In the near future, extending mosaics to include more pointings—and other instruments—is among the highest priorities of the HLA team.

The HLA currently incorporates about 4,500 ACS, WFPC2, NICMOS, and Wide Field Camera 3 (WFC3) images provided as HLSPs by independent science teams (http://hla.stsci.edu/hla_faq.html#HLSP). These HLSPs are based on fully processed data—reduced, co-added, cosmic-ray rejected, and mosaicked—and generally represent the best that can be done with Hubble data. HLSPs in the HLA are categorized by project, and can be searched, displayed, and retrieved just as all other HLA products. Planned for early 2011, HLA Data Release 5 will include new categories of data products and substantial improvements in the interface. The footprint interface will be completely revamped, to allow for zooming, panning, and dynamic changes in the products displayed. Advanced WFC3 data products will be introduced, and new mosaics released. Prototype advanced spectral products from Cosmic Origins Spectrograph and Space Telescope Imaging Spectrograph will also be available. Data Release 5 will be announced to all Hubble and MAST users; see http://hla.stsci.edu for updates.

**High-Level Science Products**

The community contributes HLSPs as fully processed images and spectra ready for scientific analysis. We encourage both individuals and teams to archive their science-ready products at MAST. Not only does this move provide a valuable service to the astronomical community, but it also showcases the original research. HLSPs are among the most downloaded products in MAST, second only to Hubble and GALEX data (Figure 3).

MAST offers a permanent home for both data and catalogs associated with all HLSPs, and provides a permanent URL to facilitate references in publications.

Our bibliographical statistics show that, of the 25 programs with the most associated papers, 72% are also associated with archived HLSPs, and more than half of the top 50 programs are associated with HLSPs.

MAST is pleased to announce the recent availability of new HLSPs, which can be accessed through the HLSP web site (http://archive.stsci.edu/hlsp).

- The ACS Treasury Survey of the Coma cluster of galaxies is a deep, two-passband imaging survey of the Coma cluster (Abell 1656), which is one of the nearest rich clusters of galaxies. The survey team recently released version 2 of the image data and version 2.1 of the associated catalogs. (http://archive.stsci.edu/prepds/coma/)

- NICMOS Legacy Archive Point-Spread Function (PSF) Library (LAPL) provides the highest quality, recalibrated, NICMOS image data for archival coronagraphic science investigations requiring PSF template subtraction. NICMOS coronography

1A visit is defined as a set of Hubble observations taken using the same set of guide stars. A visit may span multiple orbits with guide star reacquisitions.
probes the closest environments of occulted targets with Hubble's highest sensitivity at small separations and high contrast. In early 2011, MAST is planning to release data, software, and documentation from Program #11279: A Legacy Archive PSF Library and Circumstellar Environments (LAPLACE).

**Hubble Multi-Cycle Treasury Program Data**

Hubble MCT programs provide an opportunity for the community to address high-impact scientific questions requiring observing time on a scale not easily accommodated by the standard time allocation process. MCT programs have no proprietary period, and the three programs launched with Cycle 18 will release their HLSPs to the community in short order via the HLSP page in MAST ([http://archive.stsci.edu/hlsp/index.html](http://archive.stsci.edu/hlsp/index.html)). See the accompanying articles on CANDELS (H. Ferguson & S. Faber), CLASH (M. Postman), and PHAT (J. Dalcanton).

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**The Virtual Astronomical Observatory and the Institute**

Robert Hanisch, hanisch@stsci.edu, and Gretchen Greene, greene@stsci.edu

On May 15, 2010, the National Science Foundation issued a long-anticipated cooperative agreement to create a new research facility for astronomy: the Virtual Astronomical Observatory (VAO). The earlier National Virtual Observatory laid the foundation of the VAO by developing standards, protocols, and other infrastructure elements. The charter of the VAO is to promote scientific discovery with distributed data collections by making archival research much more efficient, effective, and productive.

The funding of VAO includes substantial support from NASA.

The VAO collaboration comprises the nine organizations in Table 1.

### Table 1: VAO Member Organizations

- Space Telescope Science Institute (STScI)
- The Johns Hopkins University (JHU)
- High Energy Astrophysics Science Archive Research Center (HEASARC)
- Smithsonian Astrophysical Observatory (SAO)
- National Radio Astronomy Observatory (NRAO)
- National Optical Astronomy Observatory (NOAO)
- Infrared Processing and Analysis Center (IPAC)
- California Institute of Technology (Caltech)
- National Center for Supercomputing Applications (NCSA)
VAO, LLC—a non-profit corporation—will manage the new facility. The corporation was created jointly by the Association of Universities for Research in Astronomy, Inc., which operates the Institute and NOAO, and Associated Universities, Inc., which operates NRAO and the Atacama Large Millimeter Array. Further information about the organization and governance of the VAO is at http://www.usvaoo.org/governance/.

The near-term goal of the VAO is to put useful and efficient tools in the hands of research astronomers as soon as possible. Four major initiatives are planned in the first year of operations:

- An updated portal for data search and delivery. A key component of the portal is the “directory,” which is essentially an advanced “yellow pages,” containing metadata—information about information—to describe global astronomical resources, such as images, spectra, and catalogs. The VAO portal will also incorporate image visualization, maps of spatial coverage, and navigation to other web-based science applications for the global VAO network.

- Easy access and analysis for time-series data. The focus will be on the data from the Time Series Center at the Harvard, NASA’s Star and Exoplanet Database at IPAC, and Kepler data in the Multimission Archive at Space Telescope (MAST).

- Dynamic generation and analysis of spectral-energy distributions, including editing, analysis, and visualization tools.

- Large-scale probabilistic cross-matching, in which objects in two or more catalogs are compared for positional coincidence taking into account the spatial resolution and measurement uncertainties associated with each catalog.

In addition, we have formed two science partnerships to help guide our developments. The first partnership is with the team of the CANDELS Multi-Cycle Treasury program on Hubble (see accompanying article by H. Ferguson and S. Faber). The second is with B. Madore (Carnegie Observatories), to construct a multi-wavelength, cross-matched catalog for the Small Magellanic Cloud.

The VAO facility will allocate substantial resources to operations and user support, which will regularly check the distributed data services for aliveness and compliance with standards. Also, the VAO has rigorous testing procedures to ensure that users have robust software for all common web browsers and operating systems. A capability for storing data on behalf of the community is also being developed, with an emphasis on the data—images, spectra, and tables—associated with peer-reviewed journal articles.

The Institute is heavily involved in the VAO.

Bob Hanisch, a senior scientist and member of the Science Mission Office, is the VAO director. Gretchen Greene, the chief engineer for data management in the Operations and Engineering Division, leads the Institute’s VAO-related work, and is the deputy lead for VAO product development. Maria Nieto-Santisteban, a senior software systems engineer in the Archive Science Branch, is the deputy lead for user support activities. She is focusing on defining VAO software-testing processes. Tom Donaldson, a computer scientist in the Institute’s Archive Science Branch, is coordinating the development of the VAO portal. This work will be coordinated with enhancements of the user interfaces for MAST and the Hubble Legacy Archive.

Theresa Dower, also a software engineer in the Archive Science Branch, develops and maintains the VAO directory. Ivo Busko, the primary developer of the SPECView application and a member of the Science Software Branch, is participating in the SED product development effort for VAO. Randy Thompson, a primary developer of the MAST archive, works on user testing and on implementing VAO standards.

The VAO education and outreach efforts will be led by Brandon Lawton, whom we welcome to the Institute’s Office of Public Outreach following a post-doctoral research appointment with Karl Gordon.
STScI Embraces Astrobiology and Exoplanets: The Institute for Planets and Life

Dániel Apai, apai@stsci.edu, and Jocelyn DiRuggiero, jdiruggiero@jhu.edu

The Hubble and Spitzer space telescopes were never designed to directly study exoplanets, yet they paved our way toward the detailed characterization of the atmospheres of hot jupiters. By contrast, the James Webb Space Telescope is being built and optimized in part to study exoplanets. In fact, its unique stability and sensitivity may help Webb become the first telescope to search for signs of biological activity around other stars.

But do we know what to look for, and how to find it? Simply interpreting observations of super-Earth atmospheres calls for expertise in geophysics and atmospheric physics. Planning and optimizing a search for life around other stars goes beyond this, and requires a broader set of expertise, including biology. Following a series of successful projects, astronomers at the Space Telescope Science Institute (STScI) teamed up with earth and planetary scientists and biologists from the Johns Hopkins University (JHU) to establish the Institute for Planets & Life (IPL) to prepare for the search for life. The objectives of IPL are to spark interdisciplinary discussions in the astrobiology community at the STScI, JHU, Applied Physics Laboratory, and Goddard Space Flight Center, and to facilitate the development of large-scale, multidisciplinary projects aimed at answering major questions about the origin and evolution of life, and the search for life in the universe.

Background

With funding from the NASA Astrobiology Institute, the STScI’s Director’s Discretionary Funds and JHU, the IPL group launched an astrobiology lecture series in 2009, which proved to be very popular (the video recording of the talks are accessible from the IPL website, http://astrobiology.stsci.edu). Members of the group also organized an interdisciplinary workshop on exploring the origins of water and other volatiles on Earth and other rocky planets (http://volatiles.stsci.edu).

In Fall 2010, the IPL group introduced astrobiology to the JHU curriculum, with the first course designed for advanced undergraduate and graduate students. IPL is also participating in public outreach by supporting an astrobiology exhibit for the Maryland Science Center. The expanding flurry of activities has also motivated the formation of a strong, student-organized astrobiology club.

IPL’s long-term goal is to inform the search for habitable planets by exploring the limits of life on Earth, by better understanding the planetary conditions required for life, and by searching for and characterizing exoplanets. IPL provides coordination and support for astrobiology and exoplanet-related research in the STScI’s extended community. Ultimately, IPL helps to prepare the astronomical community for using Webb for some of the most ambitious measurements in the history—the search for life beyond the Solar System.

The IPL website is at http://astrobiology.stsci.edu.
The Caroline Herschel Distinguished Visitor Program

Rachel Somerville, somer@stsci.edu

The Caroline Herschel Distinguished Visitor program sponsors extended visits to the Institute by distinguished scientists who are either members of underrepresented communities or recognized advocates on diversity and inclusion issues. The program was started in 2005. The goal is to enhance the diversity of our science community, and provide mentoring to junior scientists, particularly women and members of under-represented groups. Caroline Herschel visitors spend at least three to four weeks at the Institute—possibly broken into shorter, repeated visits—and participate in a variety of activities, including working on and lecturing about their own scientific research, giving public talks, meeting with junior staff members, and participating in panel discussions organized within the Institute’s mentoring program.

Under this very successful program, the Institute has enjoyed visits from a stellar array of distinguished scientists. (See http://www.stsci.edu/institute/sd/ch/ch_visitors.html for a list of past Caroline Herschel visitors). In 2011, we are looking forward to visits by Annette Ferguson, Priyamvada Natarajan, and Sandra Faber.

However long we live, life is short, so I work. And however important man becomes, he is nothing compared to the stars. There are secrets, dear sister, and it is for us to reveal them…

—From “Letter from Caroline Herschel (1750–1848)”
A poem by Siv Cedering (1986)
Full text at http://www.stsci.edu/institute/sd/ch/poem

Figure 1: Caroline Lucretia Herschel was born in Hannover, Germany, in 1750, and was the sister of the famous astronomer Friedrich Wilhelm Herschel. Because of deformities she suffered as a result of a childhood illness, her parents assumed that she would never marry. Her mother planned to keep her as a household servant. Nevertheless, she became interested in astronomy through her brother, and starting out as his assistant, eventually became an accomplished astronomer in her own right. She made many significant discoveries and contributions to astronomy. For example, she discovered eight comets, and the galaxy NGC 205, a companion to the Andromeda galaxy. Caroline Herschel is said to be the first woman to have earned a living by doing science.
Figure 2: Annette Ferguson, Reader at the Institute for Astronomy in Edinburgh. Her research is focused on the study of stars and interstellar gas in nearby galaxies, to gain insights into their formation histories. She makes use of observations from ground-based telescopes (Subaru, Very Large Telescope, Gemini) and Hubble, to study the connections between stellar populations, structure, and kinematics, and to probe the histories of star formation and chemical enrichment in nearby neighbors of our own Milky Way galaxy.

Figure 3: Priyamvada Natarajan, Professor in the Department of Physics and Astronomy at Yale University, is a theoretical astrophysicist interested in cosmology, gravitational lensing and black-hole physics. Her recent research projects include developing methods to probe the nature of dark energy using strong lensing by clusters of galaxies, predicting the masses of seed black holes, and studying the role of merging and obscured accretion in the growth of super-massive black holes. She is also interested in the history and philosophy of science.

Figure 4: Sandra Faber, University Professor of Astronomy and Astrophysics at the University of California, Santa Cruz, and Astronomer at Lick Observatory. Her research focuses on the formation and evolution of galaxies and the evolution of structure in the universe. Her work has spanned a broad range of topics, including characterizing the scaling relations between galaxy mass or luminosity and the internal structure (the Faber-Jackson relation and fundamental plane), measuring the masses of black holes in galactic nuclei, mapping the large-scale peculiar motions of local galaxies, and extracting information on the stellar populations of nearby early type galaxies from spectral absorption features. She also led the development of the Deep Imaging Multi-Object Spectrograph on the Keck telescopes, and has played a leading role in several important cosmological surveys, including DEEP, AEGIS, and CANDELS.

For more information about the Caroline Herschel program, see http://www.stsci.edu/institute/sd/ch.
2010 Space Astronomy Summer Program

Robert Hanisch, hanisch@stsci.edu

For a period of ten weeks this past summer—and for the 17th consecutive year—the Institute welcomed a group of some of the brightest students of astronomy and physics to work on research, technology, and public outreach projects with members of the Institute staff. I had the honor of managing the program this year, taking over from David Soderblom, who initiated the program in 1993 and provided oversight for all the intervening years. I can now say from first-hand experience how hard Dave worked on the program, and how gratifying it is to watch the students prosper during their ten weeks in residence at the Institute.

This year we had 16 students (from an applicant pool of 200) representing a diversity of colleges, backgrounds, and experience. Most were upper-level undergraduates, and several were in transition to graduate school.

The summer program concluded with a day-long seminar, with each student presenting the results of his or her work. Topics ranged from educational computer games to a variety of educational uses for the Hubble archive, and to refinement of an automated technique for image registration. Scientific presentations included variable stars discovered in the Kepler mission database and studies of stellar evolution, stellar populations, and gravitational microlensing. Other students delved into extragalactic astronomy and cosmology, studying star formation in dwarf galaxies, the background light in the Hubble Ultra-Deep Field, the initial mass function in starburst galaxies, and surprising levels of molecular hydrogen in merging galaxies.

<table>
<thead>
<tr>
<th>Student</th>
<th>College Affiliation</th>
<th>Staff Advisor</th>
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<tbody>
<tr>
<td>Mahmuda Afrin Bahdan</td>
<td>Mt. Holyoke College, South Hadley, MA</td>
<td>Claus Leitherer</td>
</tr>
<tr>
<td>Luca Borsato</td>
<td>University of Padua, Padua, Italy</td>
<td>Luigi Bedin</td>
</tr>
<tr>
<td>Melissa Butner</td>
<td>Austin Peay State University, Clarksburg, TN</td>
<td>Susana Deustua</td>
</tr>
<tr>
<td>Diane Feuillet</td>
<td>Whitman College, Walla Walla, WA</td>
<td>Kailash Sahu</td>
</tr>
<tr>
<td>Xinyi Guo</td>
<td>Pomona College, Pomona, CA</td>
<td>Paul Goudfroij</td>
</tr>
<tr>
<td>Katherine Hamren</td>
<td>Cornell University, Ithaca, NY</td>
<td>Stefano Casertano</td>
</tr>
<tr>
<td>Jessica Harris</td>
<td>Fisk University, Nashville, TN</td>
<td>Brad Whitmore</td>
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<tr>
<td>Kyle Harris</td>
<td>University of Baltimore, Baltimore, MD</td>
<td>Alberto Conti</td>
</tr>
<tr>
<td>Melodie Kao</td>
<td>Massachusetts Institute of Technology, Cambridge, MA</td>
<td>Elena Sabbi</td>
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<tr>
<td>Ethan Kruse</td>
<td>Harvard University, Cambridge, MA</td>
<td>Jason Tumlinson</td>
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<td>Pelyuan Mao</td>
<td>Lafayette College, Easton, PA</td>
<td>David Soderblom</td>
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<tr>
<td>Kristen Recine</td>
<td>Dickinson College, Carlisle, PA</td>
<td>Lisa Frattare</td>
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<tr>
<td>Sara (Alex) Sans</td>
<td>Beloit College, Beloit, WI</td>
<td>Massimo Robberto</td>
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<tr>
<td>Peter Sims</td>
<td>University of Warwick, Warwick, UK</td>
<td>Warren Hack</td>
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<tr>
<td>Tuguldur Sukhbold</td>
<td>University of Arizona, Tucson, AS</td>
<td>Harry Ferguson</td>
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<tr>
<td>Vicki Toy</td>
<td>University of California, Berkeley, CA</td>
<td>Rachel Osten</td>
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</tbody>
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The summer student program is funded in part by the Director’s Discretionary Research Fund, supplemented by individual grants held by staff members, and by departmental funds when the project is more of a functional nature. The Institute provides an intern-level salary, partial housing subsidy, travel expenses, and the use of a laptop computer on which all of the standard software packages used at the Institute are pre-installed.
The summer is not all work! This year, the students took advantage of their proximity to the cultural institutions and events of the Baltimore/Washington region, and Dave Soderblom kindly organized both a barbeque and a canoe trip. For many students, the highlight of the summer was a daytrip to tour the Goddard Space Flight Center, which included time at the visitor center as well as a visit to the instrument labs and the clean room where components of the James Webb Space Telescope are starting to come together. Thanks are due to Jim Jeletic and colleagues at Goddard for making this tour such a success.

The Institute’s summer student program is outstanding because of the hard work of many people. First, there is the selection committee (this year: Alberto Conti, Lisa Frattare, Harry Ferguson, Susana Deustua, David Soderblom, and Paul Goudfrooij), who review dozens of applications each. Pat Brown and Flory Hill provided a range of logistical support to the program, from running the on-line application system to processing time cards. Eighteen members of the science staff gave one-hour lectures on myriad aspects of astronomy, which were greatly appreciated by the students. Christine Reuter, in human resources, handled matters regarding employment, visas, and accommodations. Tracy Beck stood in as coordinator whenever I was out of the office. Thanks to all for making the 2010 Space Astronomy Summer Program such a success!

2010 Summer Students. Front rows, left to right: Kristen Recine, Mahmuda Afrin Bahdan, Luca Borsato, Alex Sans, Melodie Kao, Vicki Toy, Katherine Hamren, Xinyi Guo, Gianluca Castignani (a participant in another studentship program), Melissa Butner, Jessica Harris. Back row: Tuguldur Sukhbold, Peiyuan Mao, Kyle Harris, Peter Sims, Ethan Kruse, Diane Feuillet.
The Youth for Astronomy and Engineering (YAE) program, in the Community Missions Office at the Institute, develops and offers a variety of science- and engineering-oriented programs and activities for young people across the greater Baltimore area. New this year is our Astronomy Club (AC), which convenes middle and high school students in the Baltimore region monthly to share ideas with others who love astronomy. Club participants are given the opportunity to analyze scientific data from the Hubble Space Telescope with guidance from Institute astronomers. Rosa Diaz volunteers her time as the AC Science Lead, to share her daily professional world with these young minds, who have the potential to become our next-generation scientists and engineers. During field trips to other organizations that promote education and science, such as the Maryland Science Center, students participate in routine solar and stellar observations using high-tech amateur telescopes.

Each summer, families in the local community visit the Institute on Family Nights. This past summer, guest speakers John Grunsfeld and Brian Ferguson spoke to a packed auditorium. As Grunsfeld shared stories of his journey to become an astronaut and the work he has done on Hubble, one young audience member commented, "This is way cooler than meeting a star on TV!"

In the fall, YAE held its annual Parent & Child Evening under the Stars. This year, Heidi Hammel and Derrick Pitts were the guest speakers. The Institute’s Office of Public Outreach (OPO) led the students through a variety of hands-on activities to demonstrate the properties of light. OPO also engages the participants in an annual Young Women’s Science Forum, an all-day, hands-on activity extravaganza. These young women leave the Institute with a new level of understanding and excitement about science. Many of them return to become regular attendees of our yearly YAE program events.

The over-arching goal of the YAE program is to provide fun-filled and engaging ways to nurture budding interest in astronomy and engineering, and to endow our local community’s youth with a heightened awareness of their place in the universe.
A ghostly, glowing, green blob of gas has become one of astronomy’s great cosmic mystery stories. The space oddity was spied in 2007 by Dutch high-school teacher Hanny van Arkel while participating in the online Galaxy Zoo project. The cosmic blob, called Hanny’s Voorwerp (Hanny’s Object in Dutch), appears to be a solitary green island floating near a normal-looking spiral galaxy, called IC 2497. Since the discovery, puzzled astronomers have used a slew of telescopes, including X-ray and radio observatories, to help unwrap the mystery. Astronomers found that Hanny’s Voorwerp is the only visible part of a 300-light-year-long gaseous streamer stretching around the galaxy. The greenish Voorwerp is visible because a searchlight beam of light from the galaxy’s core illuminated it. This beam came from a quasar, a bright, energetic object that is powered by a black hole. An encounter with another galaxy may have fed the black hole and pulled the gaseous streamer from IC 2497.

Now, with the help of NASA’s Hubble Space Telescope, astronomers have uncovered a pocket of young star clusters (colored yellow-orange in the image) at the tip of the green-colored Hanny’s Voorwerp. Hubble also shows that gas flowing from IC 2497 (the pinkish object with the swirling spiral arms) may have instigated the star birth by compressing the gas in Hanny’s Voorwerp.
The globular star cluster Omega Centauri has caught the attention of sky watchers ever since the ancient astronomer Ptolemy first catalogued it 2,000 years ago. Ptolemy, however, thought Omega Centauri was a single star. He didn’t know that the “star” was actually a beehive swarm of nearly 10 million stars, all orbiting a common center of gravity. The stars are so tightly crammed together that astronomers had to wait for the powerful vision of NASA’s Hubble Space Telescope to peer deep into the core of the “beehive” and resolve individual stars. Hubble’s vision is so sharp it can even measure the motion of many of these stars, and over a relatively short span of time.

Analyzing archived images taken over a four-year period by Hubble’s Advanced Camera for Surveys, astronomers have made the most accurate measurements yet of the motions of more than 100,000 cluster inhabitants, the largest survey to date to study the movement of stars in any cluster. A precise measurement of star motions in giant clusters can yield insights into how stellar groupings formed in the early universe, and whether an “intermediate mass” black hole, one roughly 10,000 times as massive as our Sun, might be lurking among the stars.
The Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) is an observing program designed to document the first third of galactic evolution, from $z = 8$ to $z = 1.5$. It will obtain deep images of more than 250,000 galaxies with two Hubble instruments, the Advanced Camera for Surveys (ACS) and the near-infrared channel of the Wide Field Camera 3 (WFC3). It will also discover and characterize Type Ia supernovae (SNe) beyond $z = 1.5$ in order to establish their accuracy as standard candles for cosmology. The survey explores five premier sky regions, each well documented by existing multi-wavelength data from Spitzer and other facilities, and by extensive spectroscopy of the brighter galaxies. The use of five widely separated fields should mitigate the risk of cosmic variance, and should result in statistically robust, complete samples of galaxies down to $10^9$ solar masses and out to redshift $z \sim 8$.

The CANDELS science team includes ~100 investigators, 80% from the U.S. and 20% from other countries. CANDELS merges two originally separate Multi-Cycle Treasury (MCT) proposals. The combined program includes a “wide” imaging survey (depth ~2 orbits of exposure time) for three separate fields totaling ~720 sq. arcm, and a “deep” imaging survey (~12-orbit depth) for the two GOODS (Great Observatories Origins Deep Survey) regions, tiling ~60 sq. arcm in each field. The fields surveyed encompass imaging data from the Hubble Ultra Deep Field (HUDF) program (GO 11563). Thus, CANDELS offers a three-tiered strategy to efficiently sample extragalactic objects ranging from bright and rare to faint and common. It also features an extensive search for high-redshift Type Ia SNe (the first candidate is shown in Fig. 1), as well ultraviolet exposures in the GOODS northern field.

**Observing Strategy**

The search for high-z SNe Ia requires single-orbit depth in WFC3 F125W and F160W, along with a short exposure at a shorter wavelength to reject lower-redshift core-collapse SNe. Because the CANDELS fields are relatively large, with careful planning the ACS parallel exposures can usually provide the short-wavelength observations. When that is not possible, short “white-light” observations with WFC3 F350LP can provide the short-wavelength data. Scheduling the observations of each field in “epochs”—with one orbit per WFC3 tile per epoch, and with an epoch spacing of 50–60 days—will optimize the search for high-z SNe. The CANDELS/Wide survey will obtain two epochs of data per tile in WFC3, to a 5s point-source depth of $AB = 26.5–27.1$ in F125W and F160W. Follow-up observations will obtain grism spectroscopy and near-infrared photometry for SNe Ia candidates at $z > 1$, with particular emphasis on the redshift range $z > 1.5$.

Studies of Lyman-break galaxies at $z \sim 7–8$ are the major science driver for the CANDELS/Deep observations in the centers of the GOODS fields. These exposures reach 5s point-source depths of $AB \sim 27.8, 27.7, 27.4$ in F105W, F125W and F160W, with the observations spaced out over ten separate epochs. Even in the GOODS field, the existing ACS depth would be a serious limitation for identifying such distant Lyman-break galaxies. Therefore, careful tuning of the observing strategy for the GOODS fields has added 25 kilosec of F814W exposure to the existing ACS data in the deep region. The current tentative plan for the ultraviolet observations of GOODS-N is to use the portion of the orbit when Hubble is on the day-lit side of the earth to observe with the F275W and F336W filters, binning over 2×2 pixels during readout, to expected final depths of $AB \sim 28$ and 27.5, respectively.

**Release of Data and Science Products**

As is the case for all MCT programs, the CANDELS data are non-proprietary. Details of the field layouts, including exposure-maps of the planned and archival observations, are available on the CANDELS web site at [http://candels.ucolick.org](http://candels.ucolick.org).

The CANDELS team is committed to rapid release of high-level science products. We plan to release “version 0.5” images of each field within three months of each observing epoch, and “version 1.0” re-calibrated images within six months of the completion of the observations of each field. There is also a significant theory component of CANDELS, including construction of mock catalogs and mock images from state-of-the-art cosmological simulations. The public release of these products will be within a year of completion of the observations.
Continued

**Summary**

The intention of the MCT program as a whole is to enable very large projects that address multiple important science objectives, but which cannot be incorporated within the standard time allocation process. Carefully planned, thorough observations of the fields covered by this program, particularly the already well-studied GOODS fields, clearly meet these criteria. The accompanying figures and tables summarize the major science goals of CANDELS.

**Supernovae and Dark Energy**

- Test for the evolution of Type Ia SNe as distance indicators by observing them at redshifts $z > 1.5$, where the effects of dark energy are expected to be insignificant, but the effects of the evolution of the SNe Ia white-dwarf progenitor masses ought to be significant (Fig. 2).
- Refine the only constraints we have on the time variation of the cosmic equation of state, on a path to more than doubling the strength of this crucial test of a cosmological constant by the end of Hubble’s life.
- Provide the first measurement of the SN Ia rate at $z \sim 2$ to help constrain progenitor models for SNe Ia by measuring the offset between the peak of the cosmic star-formation rate and the peak of the cosmic rate of SNe Ia.

**Cosmic Dawn**

- Constrain star-formation rates, ages, metallicities, stellar masses, and dust content of galaxies at the end of the reionization era, $z \sim 6$–10.
- Improve the constraints on the bright end of the galaxy luminosity function at $z \sim 7$ and 8, and make $z \sim 6$ measurements more robust (Fig 3.).
- Measure fluctuations in the near-IR background light, at sensitivities sufficiently faint and angular scales sufficiently large to constrain reionization models.

**Figure 2:** An example of the sensitivity of the absolute magnitude of a Type Ia supernova (after correction for light-curve shape and extinction) to variations in dark energy and in supernova evolution. The relation between the cosmic mass-energy density and pressure is described by an equation of state with parameter $w = P/\rho c^2$. To low order, we can characterize the evolution of the equation of state by measuring the present-day value of $w$, and its rate of change with the expansion scale factor of the universe. That is, $w = w_0 + w_a(1-a)$, with $a = (1+z)^{-1}$. The plot shows the deviation of the apparent magnitude of a prototypical SN Ia as a function of redshift relative to a model with $w_0, w_a = -1, 0$; Three models consistent with current data are shown. The black and red curves show the effects of varying the dark energy equation of state parameter: $w_0, w_a = -0.9, 0$ (black); $w_0, w_a = -1, 0.8$ (red). The blue curve shows a model with the equation of state fixed, but with SNe Ia evolving as in the model of Dominguez et al. (2001), where the peak luminosity changes 3% per change of one solar mass in the donor star. At $z < 1$, SNe Ia measurements of distance are most sensitive to the static component of dark energy, $w_0$. In the range $1 < z < 1.5$, the measurements are most sensitive to the dynamic component, $w_a$. For $1.5 < z$, the measurements are most sensitive to evolution. If present—e.g., the changing C/O ratio of the donor star—which provides a way to diagnose and calibrate the effect of SNe Ia evolution on dark energy measurements. The error bars show the constraints at present, as for CANDELS, and if Hubble continues to collect SNe Ia at the present rate for seven more years. The inset shows the redshift distribution of SNe Ia per unit $z$ per 150 sq. arcmin per search epoch. Adding up all the search epochs, CANDELS searches will cover ~1250 sq. arcminutes. At least 8 SN Ia at $z > 1.5$ are expected.
• GREATLY IMPROVE THE ESTIMATES OF THE EVOLUTION OF STELLAR MASS, DUST AND METALLICITY AT z = 4–8 BY COMBINING WFC3 DATA WITH VERY DEEP SPITZER IRAC PHOTOMETRY.
• IDENTIFY VERY HIGH-REDSHIFT ACTIVE GALACTIC NUCLEI (AGN) BY CROSS-CORRELATING OPTICAL DROPOUTS WITH DEEP CHANDRA OBSERVATIONS. CONTRAIN FAINTER AGN CONTRIBUTIONS VIA X-RAY STACKING.
• USE CLUSTERING STATISTICS TO ESTIMATE THE DARK-HALO MASSES OF HIGH-REDSHIFT GALAXIES WITH TRIPLE THE AREA OF PRIOR HUBBLE SURVEYS.

Figure 3: Left: Constraints on the z = 7 galaxy luminosity function from early cycle-17 observations. The data points and Schechter function fit are from an analysis of WFC3/IR imaging of the HUDF (McLure et al. 2009) and include ground-based measurements at the bright end from Ouchi et al. (2009). The yellow, green and blue regions indicate the absolute magnitude ranges which the Wide, Deep and combined/UDF surveys will probe. The horizontal lines correspond to counting 10 objects, which is roughly the number needed to reduce Poisson noise below cosmic variance.

Cosmic Noon
• IMPROVE BY AN ORDER OF MAGNITUDE THE CENSUS OF PASSIVELY EVOLVING (NON-STAR-FORMING) GALAXIES AT 1.5 < z < 4. MEASURE MASS FUNCTIONS AND SIZE DISTRIBUTIONS IN THE REST-FRAME OPTICAL, MEASURE THE TREND IN CLUSTERING WITH LUMINOSITY, AND QUANTIFY EVOLUTION WITH REDSHIFT.
• USE REST-FRAME OPTICAL OBSERVATIONS AT 1 < z < 3 TO PROVIDE SOLID ESTIMATES OF BULGE AND DISK GROWTH, AND THE EVOLUTION SPIRAL ARMS, BARS, AND DISK INSTABILITIES (FIG. 4).
• DETECT INDIVIDUAL GALAXY SUBCLUMPS, MEASURE THEIR STELLAR MASSES, AND CONSTRAIN THE TIMESCALES FOR THEIR GALAXY CENTERS LEADING TO BULGE FORMATION (E.G., FIG. 4).
• TEST MODELS FOR THE CO-EVOLUTION OF BLACK HOLES AND BULGES VIA A DETAILED HUBBLE CENSUS OF INTERACTING PAIRS, MERGERS, AGN, AND BULGES, AIDED BY THE MOST COMPLETE AND UNBIASED CENSUS OF AGN FROM HERSCHEL, IMPROVED CHANDRA OBSERVATIONS, AND OPTICAL VARIABILITY (SEE FIG. 5 FOR A SCHEMATIC EXPLANATION).
• MEASURE THE REST-FRAME OPTICAL SIZE AND STRUCTURE OF PASSIVE GALAXIES UP TO z ~ 2 AND BEYOND AND COMBINE WITH ACS DATA TO QUANTIFY ENVELOPE GROWTH AND ULTRAVIOLET-OPTICAL COLOR (AGE) GRADIENTS.
• DETERMINE THE REST-FRAME OPTICAL STRUCTURE OF AGN HOSTS AT z ~ 2.
• IDENTIFY COMPTON-THICK, OPTICALLY OBSCURED AGN AT z ~ 2 AND DETERMINE THEIR STRUCTURE.
Figure 5: WFC3 structures of $z \approx 2$ galaxies, combined with GOODS multi-wavelength data, will test the merger/QSO model for bulge formation. By incorporating the morphological and SED predictions of many high-resolution simulations spanning a range of merger parameter space (e.g., stellar mass ratio, bulge/disk, orbits, dust; Hopkins et al. 2005, Lotz et al. 2008) into cosmological merger trees (e.g., Somerville et al. 2008), hierarchical models predict the relative number densities of morphologically disturbed galaxies, IR-luminous galaxies, obscured and unobscured AGN, and young bulges. The top panels show examples of simulated rest-frame $u$-$r$-$z$ images of a gas-rich major merger with AGN feedback at different merger stages (1–6). The middle and bottom panels show the predicted IR luminosity and rest-frame optical asymmetry vs. merger stage for this particular simulation. The total CANDELS volume in the 4 Gyr range $1 < z < 3$ hosts the progenitors of about 17,000 Milky-Way-mass galaxies. During this period, models predict that a typical galaxy had $\sim 2$ mergers. The timescales imply that CANDELS will have $\sim 900$ galaxies in the phase when the morphology is highly disturbed and about 900 in the AGN phase.

Figure 4. Comparison of four-orbit F775W- and two-orbit F160W-band images of selected galaxies in the UDF, highlighting the advantages of using WFC3 to study distant galaxy structure. WFC3 F160W-band images are critical for revealing the true stellar mass distribution of these galaxies, unbiased by young stars or dust extinction.
Ultraviolet Science

- Constrain the Lyman-continuum escape-fraction for galaxies at $z \sim 2.5$ (e.g., Fig. 6).
- Identify Lyman-break galaxies at $z \sim 2.5$ and compare their properties to higher-$z$ Lyman-break galaxy samples.
- Estimate the star-formation rate in dwarf galaxies to $z > 1$ to test whether dwarf galaxies are “turning on” as the ultraviolet background declines at low redshift.

Figure 6: Constraints on the Lyman-continuum escape fraction at redshift $z \sim 1.3$ from pre-CANDELS ultraviolet observations of the GOODS fields. Top: A stack of 15 star-burst galaxies at restframe $\sim 1900$ Å and the right shows the stack at restframe $\sim 700$ Å. (Reproduced by permission of the AAS: Figure 3, “A Deep Hubble Space Telescope Search for Escaping Lyman Continuum Flux at $z \sim 1.3$: Evidence for an Evolving Ionizing Emissivity,” Siana, B., et al., 2010, ApJ, 723(1), 241–250). Below: The upper limits and detections of Lyman-continuum radiation as a function of redshift from Hubble and GALEX observations (dark and light blue, purple, and green), and from ground-based observations (red and orange). It is difficult to reconcile the upper limits with the detections. If both are correct, there may be at work some interesting combination of geometrical effects, radiative-transfer effects (Inoue, 2010), and evolution. (Reproduced by permission of the AAS: Figure 5, “A Deep Hubble Space Telescope Search for Escaping Lyman Continuum Flux at $z \sim 1.3$: Evidence for an Evolving Ionizing Emissivity,” Siana, B., et al., 2010, ApJ, 723(1), 241–250.)

References

The composition of the universe has proven far more intriguing than we thought it to be, even only 15 years ago. It is a “dark” universe, where 23% of the mass-energy is made up of as yet undetected, weakly interacting, non-baryonic particles (a.k.a. dark matter, DM), and 73% is associated with as yet unknown physics that drives accelerated cosmic expansion (a.k.a. dark energy, DE). The Multi-Cycle Treasury (MCT) program presents an opportunity to make major progress on understanding the physics behind these phenomena. The MCT time-allocation committee awarded 524 orbits of Hubble time to the Cluster Lensing and Supernova Survey with Hubble (CLASH). This survey uses panchromatic imaging from the new Wide Field Camera 3 (WFC3) and the restored Advanced Camera for Surveys (ACS). The goal is to harness the power of strong gravitational lensing to test models of the formation of cosmic structure with unprecedented precision.

When combined with existing wide-field optical and X-ray imagery, CLASH observations will be a giant advance in the quality and quantity of information from strong lensing. The strong lenses in the CLASH sample—25 massive, intermediate redshift galaxy clusters—will allow us to identify hundreds of multiply imaged sources, which in turn, will allow us to challenge theoretical scenarios for the distribution of DM in clusters with ~10% precision. The CLASH images will also yield a tenfold advantage for identifying galaxies with $z > 7$, compared with any field survey of comparable area. The high magnification provided by the cluster lenses presents a unique opportunity to obtain spectra for very young galaxies that would otherwise be beyond the reach of large ground-based telescopes.

In parallel with the lensing survey, we will use both ACS and the WFC3 infrared (IR) channel to detect type-Ia supernovae (SNe Ia) in the redshift range $1 < z < 2.5$, which is uniquely accessible from space. Because the SNe Ia will be detected when these cameras are operating in parallel, they will be located far from the cluster core, where the effects of lensing are small (and correctable). Therefore, any SNe that are detected can be used to improve the limits on the redshift variation of the DE equation of state.

The CLASH MCT program combines five features that make its resulting data exceptionally well-suited to studying DM, DE, and the formation and evolution of galaxies:

- **An X-ray–selected sample of 25 dynamically relaxed, massive galaxy clusters.** This sample is large enough that observed deviations as small as 15% from the expected mean predicted DM distribution will allow us to reject models at the 99% confidence level.
- **The availability of wide-field optical and X-ray imaging for all of the clusters.** We will have full coverage of the distribution of DM and baryons.
- **The use of 16 Hubble broadband filters from the UV through the near infrared (NIR).** We will obtain photometric redshifts with an accuracy of $\Delta z \sim 0.02(1 + z)$ for all objects with AB magnitude brighter than 26.
- **A total exposure allocation of 20 orbits for each cluster.** The depth of the CLASH images is designed to achieve a five-sigma detection limit of at least 26.5 AB mag in all 16 passbands (some of the ACS and WFC3/IR images will be slightly deeper). This ensures we will be able to produce robust photo-z measurements to 26 AB mag.
- **Hubble observations spread over eight epochs for each cluster.** We will be able to search the parallel fields for SNe Ia at $z > 1$.

Figure 1 shows a preliminary CLASH image of the cluster Abell 383, based on data from the first three epochs.

CLASH will simultaneously address a wide range of scientific questions, including:

- How centrally concentrated is the DM distribution, and what implications does the distribution of concentration have for models of structure formation?
- What degree of substructure exists in the DM distribution in cluster cores?
- What is the characteristic shape of a typical cluster-scale halo of DM, and what implications does it have for the nature of DM?
• What are the characteristics (mass, composition, star-formation rate, structure) of the most distant galaxies in the universe?
• Does the equation of state of DE depend on time?
• How standard are SNe Ia? Do they show evidence for significant evolution at high redshift?
• How does the internal structure of cluster galaxies correlate with environment?

The CLASH cluster sample is large enough that it will, for the first time, place statistically significant limits on the distribution of the parameters of the DM profile in galaxy clusters. Furthermore, the precise photometric redshifts derived from the 16-band Hubble data will provide reliable distance estimates to ~6 times as many multiply lensed galaxies at $z > 1$ than could be obtained spectroscopically with 10-m class ground-based observatories. In conjunction with this exquisite multi-spectral imaging, the availability of multi-band wide-field imaging from the Subaru telescope will allow accurate measurement of the distribution of mass profiles from 10 kpc to beyond 2 Mpc. The ability to map the DM profile over a large range of radius ($r$) is critical because DM profiles steepen with radius, which provides a distinctive, fundamental prediction for cold DM. Observational constraints from both strong lensing ($r < 300$ kpc) and weak lensing ($r > 300$ kpc) are therefore needed.

Table 1 lists the 25 clusters observed in the CLASH program. Our cluster sample covers a wide redshift range, $0.15 < z < 0.9$ (with a median of $z \approx 0.4$), and spans almost an order of magnitude in mass (≈5 to $30 \times 10^{14}$ $M_\odot$), and all have X-ray temperature $T_X > 5$ keV. Twenty of the 25 clusters meet a strict criterion for symmetry of X-ray surface-brightness, and were not selected for their lensing properties. Although these clusters are solely X-ray selected, one or more giant arcs are visible in at least 16 of the 25 clusters, which indicate that the relaxed clusters in our sample have Einstein radii in the range 15–30". This assures us of high-quality strong-lensing information from Hubble imaging in the CLASH program. The existing data for 2 of the remaining clusters are of insufficient resolution to determine the presence of large arcs, and the other 5 clusters were specifically selected because they are known to have very large Einstein radii (35–55"). These 5 “high-magnification” lenses have the highest potential for the discovery of very highly magnified, ultra-high-redshift galaxies. (A significant advantage of searching for high-$z$ objects behind strongly lensing clusters is that the lens model can also help discriminate between highly reddened objects and truly distant, high-$z$ objects, because the projected position of the lensed image is a strong function of the source redshift.)

The CLASH SN search should find ~10–20 SNe Ia at $z > 1$—and potentially more; the number depends on the typical time delay between the formation epoch of the progenitor star and the epoch of the SN explosion. We expect to double the number of known SNe Ia with $z > 1.2$.

Once we find an SN in the parallel field around a cluster, we will reprogram the remaining parallel observations to gather the follow-up information—light curve and grism spectrum—needed to measure the distance. To ensure good follow-up for SNe found at the end of the observing sequence for a cluster,
we expect to use a small number of target-of-opportunity observations, or orbits from a joint reserve program with the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS).

Each cluster target will be observed using Hubble in two different orientations. Exposures for each orientation are spread out over four epochs, separated by approximately 10–14 days. This strategy enables the SNe Ia search component of our study. This observational strategy also results in eight independent epochs of imaging on the cluster core. Figure 2 depicts the resulting survey footprint around each cluster.

The total area of complete, 16-filter coverage in a cluster is 4.07 square arcmin (88% of the WFC3/IR field of view). We chose the rotation of ~30° to maximize the SNe search area while fulfilling scheduling constraints. When the observations of each cluster are completed, the cluster core will have been imaged with both ACS and WFC3 in 16 different passbands, for a total integration of ~20 orbits. Table 2 shows the exposure times in each of the 16 filters.

The parallel fields are not observed in 16 passbands—ACS parallels are taken in F775W and F850LP, and WFC3 parallels in F350LP (UVIS), F125W (IR) and F160W (IR). The typical cadence between epochs is 10–14 days. Thus, the total duration of the SNe search at each orientation is ~30–45 days.

We will observe our 25 clusters over the course of the next three Hubble observing cycles. The current plan is to observe 10 clusters in Cycle 18, 10 clusters in Cycle 19, and 5 clusters in Cycle 20. To optimize the scientific potential of our survey data, we will regularly deliver a suite of high-level science products to the Institute, for distribution to the community via the Multimission Archive at STScI. These products will include:

- Co-added images of the clusters in each passband;
- Source lists for each cluster (with pixel and celestial coordinates, and various photometric and structural parameters);
- Photometric redshift catalogs for each cluster; and
- Color jpeg images of the clusters.

With each scientific paper accepted for publication, we will release the key data used to derive the results, including:

- Wide-field Subaru image data;
- DM mass models and lens magnification maps;
- Catalog of positions and photometry of multiply lensed objects;
- Catalog of redshifts of multiply lensed objects;
- Images of de-lensed galaxies;
- Candidate high-z galaxy catalogs; and
- Spectroscopic data for galaxies in clusters and parallel fields.

### Table 1: CLASH Cluster Sample

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<th>Cluster name</th>
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Lastly, about one year after our last observation, we will release the final CLASH science archive, which will include an interactive, fully linked interface to Hubble, X-ray, Sunyaev-Zeldovich Effect, Subaru, Very Large Telescope, and Megallan datasets affiliated with our MCT program.

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PHAT

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The Panchromatic Hubble Andromeda Treasury (PHAT) is a Hubble Multi-Cycle Treasury program that will conduct a wide-area imaging survey of the stellar populations of Andromeda (M31). The goal is to establish a new foundation for interpreting observations of stellar populations across the universe and back through cosmic time.

The Importance of Nearby Galaxies

Our quest to understand the universe is anchored in our knowledge of the Local Group of galaxies. Within these galaxies, Hubble has the potential to resolve millions to billions of stars, all with common distances and foreground extinction. Those stars, along with their ancestors and descendants (e.g., molecular clouds, HII regions, variable stars, X-ray binaries, supernova remnants), provide opportunities for strengthening the foundation on which all knowledge of the distant universe is based. Local Group constraints on stellar evolution, the initial mass function, the extinction law, and the distance scale are required for interpreting observations of more distant galaxies. Most of those parameters are best constrained outside the Milky Way (MW), thus minimizing line-of-sight reddening, uncertain distances, and background/foreground confusion. External galaxies further allow one to relate the properties of the observed stars to the properties of the surrounding environment (i.e., the interstellar medium, metallicity, and star formation rate). For galaxies beyond ~1 Mpc, however, severe crowding makes the detection of the most age-sensitive stellar populations possible only in their outskirts, preventing resolved population studies of the main bodies of massive galaxies. The Local Group is thus the place where the complex processes that govern star and galaxy evolution can best be revealed in their full galactic context.

The Local Group contains four prominent galaxies that can serve as non-MW proxies for more distant galaxies: the two Magellanic Clouds, M33 (Triangulum), and M31. Of these, M31 provides the best match to the metallicity, morphology, and luminosity of the massive galaxies that dominate redshift surveys, making a wide-area systematic survey of its populations compelling. M31 shows true spiral structure, contains populations that extend to super-solar metallicity, and hosts a traditional spheroidal component. Across the universe, fully 84% of stars lie in spiral disks (58%) or bulges (26%; Driver et al. 2007), and more than 3/4 of all stars today have metallicities within a factor of 2 of solar (Gallazzi et al. 2008). These factors make M31 a far more relevant laboratory than the Magellanic Clouds. Moreover, M31 contains the vast majority of the stars in the Local Group outside the MW, offering the opportunity to generate samples of sufficient size that Poisson statistical errors are negligible, and even rare phenomena are well represented. Finally, the stars in M31 are

Figure 1: The image above shows the locations of the PHAT “bricks,” superimposed on a GALEX near-ultraviolet image. Each brick consists of a 3-by-6 mosaic of WFC3/IR pointings, with overlapping WFC3/UVIS and ACS/WFC coverage. Bricks 1, 9, 15, and 23 will be completed in winter 2011.
bright enough to be accessible spectroscopically. Therefore, we can augment photometric observations with an extensive program of spectroscopy, to provide measurements of the kinematics, metallicities, spectral types, and physical parameters of star clusters and stars on the upper main sequence, asymptotic giant branch, and red giant branch.

The PHAT Survey

The PHAT survey covers roughly 1/3 of M31’s area, from the bulge to just beyond the end of the star-forming disk (see Figure 1). The data cover wavelengths from the ultraviolet (UV) through the near infrared (NIR) with sufficient coverage to both isolate key features of the color-magnitude diagram and to disentangle stellar parameters and extinction for individual stars. The imaging reaches the maximum depth possible with Hubble’s resolution in most filters, and is accompanied by extensive spectroscopy for thousands of stars.

The PHAT Hubble observing plan calls for tiling a large contiguous area of M31 with 23 “bricks,” each of which is comprised of 18 pointings of WFC3/IR (the infrared channel of the Wide Field Camera 3), arranged in a 3-by-6 array. At each pointing, one orbit is devoted to imaging in filters F275W+F336W with the ultraviolet-visible (UVIS) channel of WFC3 in primary, and F814W with the Advanced Camera for Surveys (ACS) running in parallel. Then, a second orbit images the same region in F110W+F160W with WFC3/IR in primary, and ACS again running in parallel with F475W.

Observations of each brick are carried out in two observing “seasons,” approximately six months apart. The first season completes a 3-by-3 pointing pattern, producing a half brick with complete ACS coverage, and an adjacent half brick with IR plus UVIS coverage. In the second season, the telescope rotates through 180 degrees, such that the primary WFC3 observations now cover the first season’s ACS observations, and parallel ACS observations now cover the first season’s WFC3 observations. This plan completes the six-filter brick coverage with the highest possible observing efficiency.

The bricks are oriented to maximize the number of days during which observations can be scheduled. The use of two brick orientations further increases the scheduling opportunities and minimizes the impact on other observing programs. The bricks are placed in two strips and numbered such that Brick 1 covers the bulge, with odd number bricks extending along the major axis. Targets are named according to the brick number and the field number within the brick (where the field number goes from 01 to 18, in a consistent pattern corresponding to the individual pointing centers within each brick). Observations for the first halves of Bricks 1, 9, 15, and 21 are now in the archive, and the overlapping filter coverage should be completed by February 2011. (See Figure 2 for a small subregion of Brick 15.)

We expect to release over 50 million photometric observations based on these data by summer 2011. We have also recently completed spectroscopy for more than 3000 sources within the survey area; the resulting velocities, line strengths, and spectral classifications will be released as high-level data products by the end of the PHAT program.

Conclusions

The legacy and scientific values of our survey are rich and diverse. The proposed survey will (1) provide the tightest constraints to date on the slope of the initial mass function above five solar masses as a function of environment and metallicity; (2) provide a rich collection of star clusters spanning wide ranges of age and metallicity, for calibrating models of cluster and stellar evolution; (3) characterize the history of star formation as a function of radius and azimuth within M31, revealing the spiral dynamics, the growth of the galaxy disk and spheroid in process, and showing the role of spiral arms, tidal interactions, and stellar accretion; (4) create spatially resolved UV-through-NIR spectral energy distributions of thousands of previously cataloged X-ray binaries, supernova remnants, Cepheid variable stars, planetary nebulae, and Wolf-Rayet stars, allowing full characterization of these sources; and (5) provide excellent probes of the gas phase and its interaction with star formation, by using sub-arcsec extinction mapping, and by comparing parsec-scale gas structures to the recent history of star formation and stellar mass loss.

PHAT will provide a fundamental baseline for characterizing sources in transient surveys (e.g., by the Panoramic Survey Telescope & Rapid Response System) both by direct identification of counterparts, or, when the counterpart is undetected even at Hubble’s depth and resolution, by associating transients with the properties of the surrounding stellar population.
Each image from the Hubble Space Telescope provides a wealth of knowledge about the spatial distribution of light in an astronomical scene. Now, imagine every distinct region in a Hubble image is accompanied by a spectrum that provides additional information on the motion, composition, or physical state of the source region. Such integral-field spectroscopy (IFS) is precisely what the 3D data from an integral-field unit (IFU) provides! Today, IFU-type instruments are common and in use at many ground-based observatories. The next generation of large telescopes—both on the ground and in space—will include IFUs in their instruments, including NIRSpec and MIRI on the James Webb Space Telescope, and first-generation instruments for the European Extremely Large Telescope and the Thirty Meter Telescope. IFUs have come of age.

In late October 2010, the Institute hosted a timely workshop entitled “IFUs in the Era of JWST.” It was the first major international conference on IFS in the U.S. in the last decade, and more than 60 astronomers from four continents attended. The workshop offered three days of presentations and discussions of IFS techniques, progress in instrument development, discussion of 3D data viewing and analysis—and new scientific results. The workshop consisted of more than 40 talks from experts in the IFS community. Highlights include:

- Roger Davies (U. Oxford) presented a global overview of IFU capabilities, and showed how IFS observations are reshaping our thoughts about elliptical (E) and lenticular (S0) galaxies. Studies with 3D IFS have revealed that early-type galaxies exhibit distinct large-scale motion, whereas astronomers had expected velocity distributions dominated by random motion. Furthermore, many weakly rotating E/S0 galaxies exhibit kinematically decoupled cores—regions with unique, sharply differentiated motion—which imply past merger activity in the systems.

- Natasha Forster-Schreiber (Max-Planck-Institut für Astrophysik) gave the regular Institute colloquium the week of the IFU workshop—a talk entitled “The Growth of Galaxies at z 2: Insights from IFU Surveys.” She presented results from the Spectroscopic Imaging Survey in the Near-infrared with SINFONI (SINS) galaxy survey. SINFONI is an IFS instrument on the Very Large Telescope of the European Southern Observatory. Her research suggests that the majority of galaxies at z 2 are large, rotating, and often gas-rich disks. Insights into these systems are improving our understanding of how massive galaxies gain mass over cosmic time.

- Torsten Böker (ESA), who is NIRSpec deputy project scientist and a member of the MIRI instrument science team, presented the specifications for the NIRSpec and MIRI IFUs on Webb. MIRI will always acquire medium-resolution spectroscopy with the IFU. The IFS capabilities with Webb should reveal the motions and physical conditions in galaxies with unprecedented sensitivity, and help us better understand how galaxies formed in the early universe.

- James Larkin (UCLA) gave an overview of IFS capabilities planned for the next era of large ground-based telescopes, and highlighted the IFS instrument that his team plans to build for the Thirty Meter Telescope.

During group discussions on viewing and analyzing IFS data, participants expressed a variety of opinions. This diversity reflects the wide range of science applications for IFS, as well as the complexity of IFS data structures. Researchers are still experimenting with optimal methods, and hope that commonly used tools will emerge.

Archived versions of all the presentations at this workshop are available from the archive link for the week of Oct. 25, 2010, at https://webcast.stsci.edu/webcast/

Astronomical conferences are held in a variety of locations, ranging from big city convention centers to college campuses, science institutes to observatories. Rarely has a meeting been more evocatively situated than the recent “Science with the Hubble Space Telescope III. Two Decades and Counting,” which was held in Venice in October 2010. Venice is famous for its classic combination of arts and science, and Hubble is established as an unsurpassed source of science and beauty.

The Venice meeting was the third major meeting on Hubble sponsored by the European Space Agency (ESA). The first was in Sardinia in 1992, two years after the Hubble launch. The second was in Paris in 1995, following the first servicing mission and repair of the telescope’s spherical aberration. The Venice meeting marked Hubble’s 20th year in orbit, now operating with fifth-generation instruments. Many of the speakers at the meeting were only school children when Hubble was launched, which gave perspective to the sense of history inspired by the subject and venue.

The Scientific Organizing Committee designed the programme to achieve a balance between the past, with a celebration of the extraordinary results obtained by Hubble so far in its lifetime, and the future, with enthusiastic anticipation for science yet-to-come, following the successful Servicing Mission 4 (SM4).

David Southwood, ESA Director of Science and Robotic Exploration, opened the conference, noting that Hubble paved the way for several other collaborations between ESA and NASA, including the future James Webb Space Telescope. David Leckrone and Duccio Macchetto recalled the early days of Hubble, from both the U.S. and European perspectives. Adding to the nostalgia were several before-and-after image pairs, highlighting the successful repair of the telescope in the first servicing mission.

One full day was devoted to new results following SM4. Randy Kimble and Robert O’Connell talked about Wide Field Camera 3 (WFC3). A preview of future WFC3 results was provided by overviews of three Multiple Cycle Treasury (MCT) programs: the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; Sandra Faber), the Cluster Lensing and Supernova Survey with Hubble (CLASH; Marc Postman), and the Panchromatic Hubble Andromeda Treasury (PHAT; Julianne Dalcanton).

James Green discussed the Cosmic Origins Spectrograph (COS), and showed new findings on reionization. Cynthia Froning highlighted progress sorting out the cosmic web—the vast foam-like structure of cosmic matter on the largest scale. After only one year in operation, COS has increased the number of Lyman-alpha sightlines by a factor of ten. Jason Tumlinson discussed searches for the missing baryons, and Christopher Thom and John Stocke talked about probing the outer halos of nearby galaxies.

The MCT Program is a reminder of changes in the conduct of astronomy in the Hubble era, particularly steps to counteract the tendency of telescope allocation committees to spread observing time over many small programs. Before launch in 1990, an Institute advisory committee recommended that a sizable fraction of Hubble observing time be reserved for large programs. The first key projects were directed at the Hubble constant ($H_0$), quasar absorption lines, and a medium-deep cosmic survey. In 1995, Director Robert Williams allocated 150 orbits to the Hubble Deep Field (HDF), which set a precedent for creative use of the director’s discretionary time, distributing large data sets to the public immediately—without the standard one-year proprietary period—and releasing a finished dataset and catalog only a few months after the observations are taken. Another important side effect of such large programs has been the development of state-of-the-art tools—like DRIZZLE, invented for the HDF. (The DRIZZLE algorithm can combine multiple stacks of dithered, geometrically distorted, undersampled image frames.) Attendees were polled about optimizing use of Hubble in the future. Several in the audience...
A panel of six distinguished scientists contemplated the question: “What have we missed?” The consensus view was assurance about the future: that *Hubble* has tackled a rich variety of interesting and important questions in the past and is destined to continue. Other ideas included preparatory research for future *Webb* observations, and a fresh look at special aspects of the *Hubble* archive, such as the extensive time-resolved information. Another discussion point was whether the proprietary data policy should be reconsidered for certain types of projects—for example, should the default for large projects be no proprietary time, as for Treasury programs.

Short talks highlighted the amazing range of *Hubble* science: from the detection of a sub-kilometer-sized Kuiper belt object by stellar occultation using the Fine Guidance Sensors (Hilke Schlichting; see “Smallest Kuiper Belt Object Ever Detected” in this *Newsletter*), to the confirmation of a planet detection in the disk around Formalhaut (Paul Kalas), to high precision color-magnitude diagrams showing multiple-generation populations in globular clusters (Giampaolo Piotto), to the buildup of early-type galaxies via minor mergers (Robert O’Connell), to searching for high-redshift galaxies via gravitational lensing (Marc Postman).

While there was a clear sense of history at the meeting, the focus was on the future. Thanks to SM4, *Hubble* is at the peak of its research power, with detectors that are several orders of magnitude more powerful than in its early days. Nobel laureate John Mather put *Webb* capabilities and scientific goals in context for the conference attendees. That *Webb* will make a leap in capability as huge as *Hubble’s* was an inspiring thought for meeting participants.

John Grunsfeld gave a public talk on the *Hubble* story, particularly how SM4 enabled the scientific observations that astronomers are now performing. The question-and-answer session following Grunsfeld’s talk was intriguing because of the translations provided between Italian and English. The Venetian audience, probably never previously exposed to a first-person account of a space mission, was interested in the human factors and emotional implications of being in space.


On the last day of the Venice meeting, the future of *Hubble* was discussed in relation to other missions and facilities. NASA and ESA officials presented the plans for their future space programs. The conference concluded with some ambitious thoughts about the distant future and what space astronomy could accomplish in the next two to three decades, with closing remarks by Roger Davies. Of all the *Hubble’s* observations, Davies selected the characterization of exoplanetary atmospheres as perhaps the most impressive *Hubble* science result to date.
Final Thoughts

_Hubble_ science is sometimes divided into two types. The first derives from questions that _Hubble_ was designed to solve, and in almost all cases, _did_ solve. A good example of this type is the refinement in $H_0$ (and its inverse, the age of the universe), Lucas Macri reviewed this topic and described the cutting-edge research now enabled by WFC3. He reminded the audience of the factor-two discrepancy between the value of $H_0$ of deVaucoulers and van den Bergh (100 km s$^{-1}$ Mpc$^{-1}$) and the value of Sandage and Tamman (50 km s$^{-1}$ Mpc$^{-1}$). Figure 3 shows how _Hubble_ ended this longstanding debate, with both the Freedman et al. (2001, ApJ, 553, 47) and Sandage et al. (2006, ApJ, 653, 843) values agreeing within the errors. Macri also described the current work of his own group (Riess et al. 2009, ApJS, 183, 109), which is striving for 2–3% accuracy in $H_0$ using WFC3 to observe Cepheid variable stars in the near infrared.

The second type of _Hubble_ science is the unexpected discovery. Here, the fact that _Hubble_ is a multi-use telescope—rather than designed for a specific question—comes into play. Over the past 20 years, the surprises have often stolen the show, as a variety of speakers illustrated: comet impacts on Jupiter (Harold Weaver), the discovery of dark energy (Sandra Faber, Marc Postman, Lucas Macri), the ability to detect atmospheres of transiting planets (Giovanna Tinetti). None of these examples were envisioned when _Hubble_ was being planned and built.

We sometimes think back to what we thought our careers would be like when we were graduate students—possibly envisioning a rather sedate, small college environment, teaching introductory astronomy, or spending nights on a cool mountain top peering at the universe through a telescope. Contrast this with the roller-coaster ride that has been _Hubble_: the budget battles; the dramatic discovery and brilliant cure of spherical aberration; the epochal importance of the _Hubble_ success to NASA as a whole; the arresting images that have garnered international attention and public support; and the sheer magnitude and variety of the questions _Hubble_ is addressing, from the formation of earthlike planets to galaxies at the edge of the universe.

While it was never easy, we feel privileged to be part of the _Hubble_ story.

Acknowledgements

All the small details that made this conference so successful were orchestrated by an efficient local organizing committee, chaired with excellence by Elena Dalla Bontà from the nearby University of Padua.

Dr. Robert Fosbury

The Space Telescope European Facility (ST-ECF) organized the Venice meeting, as it has done in the past for ESA-sponsored _Hubble_ meetings. The ST-ECF is a small group of dedicated and innovative people, who succeeded through the years in keeping _Hubble_ visible in Europe. Because the ST-ECF closed at the end of 2010, the Scientific Organizing Committee thought it appropriate to celebrate ST-ECF’s outstanding contributions by dedicating the conference to Dr. Robert Fosbury, ST-ECF head, who retired from ESA at the end of the year.
Closure of the ST-ECF

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Following decisions made by both ESA and ESO during the last few years, the Space Telescope European Coordinating Facility (ST-ECF) closed and ceased operations on 31 December 2010. Established as a joint venture between these two organizations in 1984, the ST-ECF has worked in close collaboration with the Space Telescope Science Institute in Baltimore to support European users of Hubble and to provide significant contributions to the operation of the observatory and its instruments. The history of the activities of the ST-ECF group in Garching, Germany, is captured in the 48 issues of the ST-ECF Newsletter (http://www.spacetelescope.org/about/further_information/newsletters/).

Information resulting from the group’s instrument science activities has been transferred to the Institute, and is available from www.stsci.edu. Of topical interest, this includes all the work concerned with slitless spectroscopy obtained with NICMOS, ACS, and WFC3.

The Hubble outreach activities, started in response to a request from NASA more than a decade ago and delivered through www.spacetelescope.org, will continue at a substantial, but somewhat more modest, level with the continued involvement of the ESO education and Public Outreach Department (ePOD) and a financial contribution from ESA.

Until very recently, it was intended to keep the European Hubble Data Archive at ESO, where it was originally the model for the development of the ESO Science Archive Facility. The intention now, however, is to create a European access point for Hubble data at the European Space Astronomy Centre (ESAC) in Spain. ESO will cooperate as far as possible in achieving this transfer in a way that avoids an interruption in public availability in Europe.

Arrangements for the travel of European scientists to the USA on ESA Hubble business—previously dealt with by the ST-ECF—will now be handled by ESA’s Hubble Mission Manager at the Institute.

The European engagement with the Hubble project and its outstanding record of scientific productivity was recently marked by a conference, exhibition, and art installation in the city of Venice, hosted by the Istituto Veneto di Scienze Lettere ed Arti and organized in conjunction with the Institute. (See accompanying article on this meeting.)

John Huchra: An Appreciation

Marc Postman, postman@stsci.edu

Each one of us has an “astronomical parent”—that person who took us under their wing and taught us how to be an astronomer, how to do research, how to take the spark of an early idea and transform it into new knowledge. I was very fortunate to have two astronomical parents, Margaret Geller and John Huchra.

When I first met John in 1981, he was what you would call an “observer’s observer.” He loved being on the mountaintop, telescope controls in his hands. He regaled all us grad students with his observing adventures and wisdom. He infected us with his enthusiasm for discovery and amazed us by his skills at finding exciting problems to solve. The 1980s were especially exciting, as John was one of the co-discoverers of the “cosmic web,” which is now so fundamental to our understanding of the structure of the universe. But most of all, I recall John’s generosity and warmth. In the 29 years that I knew him, I never saw him behave spitefully or with malice towards anyone. And that is one of the most important things that John taught me—that you could succeed as a scientist and still be a mensch! That, and how to play a mean game of eight-ball on a cloudy night.

John became a husband and a father later in life. And it was good to see how much joy his family life brought him. Alas, Rebecca and Harry have lost their husband and father way too soon. I ask myself—how does one cope at times like these? My father, Neil, once said, “Children are the living messages we send to a time we will not see.” I am one of John’s living “astronomical” messages, and his spirit, his joy of science and for life live on in me, and in many of you, as we continue our exploration of the universe.

To my teacher, my friend, and our colleague, we will miss you very much.
Edward Weiler on the Origins of Hubble Servicing

David Soderblom, soderblom@stsci.edu

Edward Weiler, NASA Associate Administrator for the Science Mission Directorate, visited the Institute last summer on the last day of the Calibration Workshop. Ed spent nearly 20 years (1979–1998) at NASA headquarters as Program Scientist for Space Telescope (starting before the “Hubble” was added). In that role, he was instrumental in ensuring the long-term operations of Hubble, the variety of science done with the telescope, and the importance of outreach efforts.

Perhaps more than any other single factor, the success of Hubble is due to regular visits by astronauts. They have repeatedly repaired and upgraded its support systems, and installed five generations of ever-more-powerful scientific instruments. While the planning for servicing may seem like an inevitability now, it was far from obvious in the early 1980s, as Ed told the audience that gathered to hear him—and to get their copies of his recent book, Hubble: A Journey Through Space and Time, signed. Thirty years ago the space shuttle had just started to fly, but the costs and difficulties of shuttle missions to Hubble were becoming apparent. At first, early servicing plans called for a return to Earth for a complete rebuilding, but it was soon clear that this was not realistic. Nor was the plan for a notional Orbiting Maneuvering Vehicle to ferry Hubble to a servicing bay in the space station.

Ed Weiler played a key role in defining Hubble’s successful servicing program, and in seeing that the planning of the second generation of scientific instruments—Wide Field Planetary Camera 2 (WFPC2), Space Telescope Imaging Spectrograph, and Near Infrared Camera and Multi-Object Spectrograph—started well before the telescope was even launched. Indeed, the fact that WFPC2 was under construction afforded an opportunity to incorporate corrective optics inside the instrument, in time for the first servicing mission in 1993. This was a crucial step in solving the problems created by spherical aberration in Hubble’s primary mirror.

During his visit to the Institute, Ed had a chance to meet with old friends and to tell us about how early Hubble experiences have influenced astronomy well beyond Hubble itself. A notable example was the transfer to the National Science Foundation (NSF) of surplus CCDs from the first-generation Wide Field and Planetary Camera. NSF distributed the CCDs to ground-based observatories, resulting in a mini-revolution in contemporary astronomy even before Hubble’s launch.
The Kuiper belt, a region of small, icy bodies thought to be left over from the formation of the solar system, extends from the orbit of Neptune to more than 5 trillion miles from the Sun. It contains numerous bodies called Kuiper belt objects (KBOs), the most famous being Pluto and its moons. Due to their small size, only the larger KBOs can be detected with direct imaging. Smaller objects, however, can be detected indirectly when they pass in front of a background star and partially obscure the stellar light. These events, called occultations, should last only several tenths of a second for such small and distant KBOs; therefore this method of detection requires a dedicated observing plan that carefully monitors many stars. Hilke Schlichting, of the Canadian Institute for Theoretical Astrophysics in Toronto, and her collaborators devised an unconventional way to detect these tiny KBOs: by extracting their signatures from previously collected Hubble engineering data.

Hubble has three optical instruments called Fine Guidance Sensors (FGSs) that provide high-precision navigational information to the space observatory’s attitude control system. They do this by exploiting the wave nature of light to make extremely precise measurements of stellar positions. Schlichting and her team determined that the FGS instruments are also sufficiently sensitive to detect the faint signal of a KBO passing in front of a star. Such an event would cause a brief occultation and a diffraction signature in the FGS data as the light from the background guide star is bent around the intervening foreground KBO.

The researchers selected 4.5 years of FGS observations for analysis. During this period Hubble’s FGSs spent a total of 12,000 hours observing along a strip of sky within 20 degrees of the solar system’s ecliptic plane. This is where scientists expect to find the majority of KBOs. Schlichting and her team analyzed the FGS observations of 50,000 guide stars in total. Scouring the huge database, they found a single 0.3-second-long occultation event. Detection was only possible because the FGS instruments sample changes in starlight 40 times a second. The researchers found the KBO at an inclination of 14 degrees to the ecliptic, and assumed the KBO was in a circular orbit. The KBO’s distance was then estimated from the duration of the occultation, and the amount of dimming was used to calculate the size of the object.

The tiny body appears to be just over a half mile — or approximately 1 kilometer — across and is located 4.2 billion miles away. The object is so small and distant that it is 100 times dimmer in reflected sunlight than what Hubble can see directly. In fact, the smallest KBO previously seen in reflected light by any telescope is roughly 30 miles across, or 60 times larger.

This small KBO represents a missing link between micron-sized dust particles and larger KBOs in the Pluto-size class of 1,000 km. Researchers have long suspected that these bodies exist, but previously lacked proof for objects of this size. They are believed to be the result of collisions among the members of the original Kuiper belt population. The detection of only one event actually reveals a deficit of sub-kilometer-sized objects compared with the population extrapolated to exist from the known number of large Kuiper belt objects. This implies that sub-kilometer-sized objects are undergoing collisional erosion. These small bodies are likely the source material for the Kuiper belt.
Dr. Hilke Schlichting is a Hubble postdoctoral fellow at the University of California, Los Angeles. Her work focuses on planet formation, particularly the dynamical and physical properties of the Kuiper belt and Oort cloud populations, and the information they reveal about the formation of the solar system. Her past research has included the origins of planetary spins and the velocity distribution of planetesimals and protoplanets during various stages of their formation. Schlichting received her B.A. and M.S. in physics from the University of Cambridge and her Ph.D. in astrophysics from the California Institute of Technology. She was born in Bad Soden, Germany, and has lived in Germany, Japan, England, Canada, and the United States.

for comets, and additional observations may shed light on whether comets are solid, like pieces of rock, or more closely resemble collections of rubble held together by gravity.

In an effort to uncover more small KBOs, the team plans to analyze the remaining FGS data for nearly the full duration of Hubble operations since its launch in 1990. The discovery of additional objects could provide direct evidence for the theorized population of approximately 10,000 bodies thought to supply the number of observed Jupiter-family comets—those with periods of less than 20 years. Such research is a powerful illustration of the capability of archived Hubble data to enable new and important discoveries.

Further Reading
Early a century ago, when considering the cosmological implications of his monumental theory of General Relativity (GR), Albert Einstein realized that his equations needed a small adjustment. It was the widely held view of astronomers in 1917 that although planets, stars, and assemblies of stars all move with respect to each other, the universe as a whole is static—neither contracting nor expanding. Einstein's original formulation of GR did not permit such a stable universe. However, the famous physicist found that the addition of a constant term to his equations produced one. This "cosmological constant" had the effect of a repulsive force that kept the universe from collapsing under its own weight, like a house of cards.

In 1929, astronomer Edwin Hubble found a relationship between the galaxy distances he could measure and the velocities of those same galaxies determined by others. In short, virtually all galaxies were found to be receding, and the further away a galaxy is located from us, the faster it recedes. More specifically, galaxy distance is proportional to velocity. This relationship between velocity and distance—now called the Hubble constant, or \( H_0 \)—meant the universe was expanding, not static. No additional mathematical help was needed to shore it up from collapse. Einstein then referred to the cosmological constant as his "biggest blunder."

In 1998, two research teams used multiple (mostly ground-based) telescopes to look deep into space—and hence far back in time—in order to measure the rate at which the universe's expansion slows down under the relentless pull of gravity. In effect, they were searching for the change of the Hubble constant with cosmic time. The key question they were trying to answer—one which had been on the forefront of astrophysics for decades—was whether gravity is ultimately strong enough to halt the expansion. If so, the universe would ultimately fall back upon itself in a "big crunch." If not, the expansion would continue forever.

One team was led by Adam Riess (Space Telescope Science Institute and the Johns Hopkins University) and Brian Schmidt (Mount Stromlo Observatory). The other was led by Saul Perlmutter (Lawrence Berkeley National Laboratory). Both studies came to the same stunning conclusion. Independently, these two research teams discovered that the universe is not slowing, but actually is in the process of accelerating. This unexpected condition was attributed to an unknown repulsive force they named "dark energy." Dark energy seems to behave like Einstein's cosmological constant due to the presence of energy in "empty" space, but further observations were needed to see if it truly remained stable over time.

Using the Hubble Constant to Characterize Dark Energy

One of the major reasons for launching the Hubble Space Telescope in 1990 was to more accurately measure the Hubble constant, an essential ingredient in determining the age, size, and fate of the universe. Until the launch of the Hubble telescope, the range of measured values for the expansion rate spanned from 50 to 100 kilometers per second per megaparsec—an unacceptably large factor of two. (A megaparsec is the unit of distance commonly used to measure the distance between galaxies. It equals one million parsecs or 3.26 million light-years.) By 2001, the team for the Hubble...
Space Telescope Key Project on the Extragalactic Distance Scale had refined the value of the Hubble constant to $72 \pm 8$.

In 2003, Riess and his team used the Advanced Camera for Surveys on Hubble to probe dark energy and acceleration to greater distances and more ancient epochs in the universe’s history than had been possible in 1998. What Riess and colleagues found was that earlier than about five billion years ago, the universe was doing what had originally been expected—it was *decelerating* under the influence of gravity. However, at five billion years ago, the expansion underwent a transition from deceleration to the acceleration observed in the more local universe and reported in 1998.

The repulsive force of dark energy and the attractive force of gravity were each present on both sides of the transition. In the earlier times gravity, particularly the gravity of dark matter, which accounts for most of the universe’s mass, was the stronger of the two—it was “winning the battle” against dark energy. However, as space continued to expand, the gravitational tug of diluted dark matter became weaker than the push of dark energy. Since the transition period five billion years ago, the universe has been speeding up—dark energy is now dominating the contest between these two forces.

Scientists know with some certainty that nearly three-quarters of the energy density of the local universe is in the form of dark energy. However, they do not know what it is. In 2009, to better characterize dark energy, Riess and his SH0ES (Supernova H0 for the Equation of State) Team used Hubble to refine the value of the universe’s expansion rate to an accuracy of 4.5 percent. The new value is 74.2 kilometers per second per megaparsec, with an error margin of ±3.6. This means that for every additional million parsecs a galaxy is from Earth, it is on average receding 74 kilometers per second faster. This new, more accurate value of the Hubble constant was combined with 2008 data from NASA’s *Wilkinson Microwave Anisotropy Probe* (*WMAP*) that measured the distant, early universe based on fluctuations in the cosmic microwave background, to test and constrain the properties of dark energy.

The refined Hubble constant continues to imply—now with three times as much confidence than before—that dark energy may really be the steady push on the universe that Einstein imagined, rather than something more ephemeral. By tracing the expansion history of the universe between today and when the universe was only approximately 380,000 years old, the Riess team was able to place limits on the nature of the dark energy that is causing the expansion to speed up.

The discovery of dark energy, the refinement of the Hubble constant, and the implications of that refined value for dark energy are tremendously important to the astrophysics of the new millennium. It is critical, however, to realize that these discoveries rely on observational evidence which is extremely challenging to gather and interpret accurately—in particular, how we measure cosmic distances.
Cosmic Tug of War

What astronomers know today about the expansion-rate history of the universe is illustrated in this figure. The gravitational force from matter, including dark matter, is depicted as a stretched rubber band—the force is inward and has the effect of slowing the expansion. Dark energy, on the other hand, is rendered as a compressed spring—it pushes outward and exerts a repulsive force, accelerating the expansion. Whether deceleration or acceleration occurs depends on the difference, or net force—attractive (inward) or repulsive (outward).

The main body of the figure shows four “time slices” over history using the stretched rubber band and compressed spring graphics to characterize the relative strengths of these two opposing forces. In the earliest time slice (lowest in the figure) more than five billion years ago, the universe was smaller and more dense than it is today; gravity from matter opposed dark energy and was actually the stronger force. The net force was attractive, as indicated by the two inward-directed arrows, and the universe was expanding but slowing down. Approximately five billion years ago, a transition occurred at which the two forces were equal and cancelled each other out. The net force was zero, as indicated by the lack of arrows. At this point in time, the universe was expanding, but at a constant velocity. In the upper two time slices—the lower representing the present universe and the upper portraying its future—dark energy dominates the tug of war, exceeding the reduced gravitational force in a less-dense universe. As indicated by the outward-directed net force arrows, this repulsive force accelerates the expansion of the universe.

The Hubble data analyzed by the SHOES Team is consistent with—but does not yet prove—the idea that dark energy is constant over cosmic time. Gravity’s influence, however, is steadily declining.
Measuring Distance Using Standard Candles, and Strengthening the Cosmic Distance Ladder

Astronomers can use simple geometry to triangulate the distances to the nearest stars by studying how they shift against background stars as the Earth orbits the Sun. But to gauge deeper distances, scientists depend on finding so-called “standard candles”—stars or other objects whose intrinsic luminosities are known and thus their distances can be derived from their apparent brightnesses.

Among the most reliable of these candles is a special class of pulsating stars called Cepheid variables. Cepheids brighten and dim in a predictable pattern over a period of days to weeks, like slowly winking lights on a Christmas tree. The more luminous they are, the longer their cycles. Through their regular, slow winking, such stars in a galaxy broadcast their luminosities and hence, their distances. As critical as they are, Cepheids by themselves cannot take us to the most remote distances in mapping out the complete history of universal expansion—they are simply not bright enough.

Therefore astronomers must step outward by means of a “distance ladder,” a tool that links together progressively longer-range distance indicators by using each rung of the ladder to calibrate the next. The nearby Cepheids are first calibrated, and then used to calibrate brighter standard candles in more distant galaxies. Unfortunately, the luminous, more useful candle sources are rare and difficult to find in sufficient numbers. Many astronomers currently use a kind of exploding star known as a Type Ia supernova, brilliant enough to be seen across up to two-thirds of the observable universe. Type Ia supernovas all explode with nearly the same amount of energy and therefore have almost the same intrinsic luminosity (the small differences in luminosity can be calculated by detailed examination of their “light curves”—the rapid rise and then slow fall-off of the observed light). Thus, these supernovas are reliable distance indicators for more distant measurements as long as their “rung of the ladder” is calibrated against the others.

Riess’s 2009 study used Hubble’s Near Infrared Camera and Multi-Object Spectrometer (NICMOS) and the Advanced Camera for Surveys (ACS) to observe more than 100 Cepheid variables in a nearby cosmic mile marker, the galaxy NGC 4258—also known as Messier 106 in Ursa Major. The SH0ES team also used NICMOS and ACS to observe 150 Cepheid variable stars across six galaxies that had hosted well-observed Type Ia supernovas. These included the galaxies NGC 3370 (seen on page 120) and NGC 3021.

In galaxy NGC 4258, astronomers have also found clouds emitting radio waves at a frequency characteristic of water vapor circling the center of the galaxy. By tracking the speeds and motion across the sky of these clouds with high-resolution radio observations, they determined the distance of this
Spiral galaxy NGC 3021 was one of several host galaxies of recent Type Ia supernovas used to refine the measurement of the universe’s expansion rate. Hubble made precise measurements of Cepheid variable stars in the galaxy, highlighted by green circles in the four inset boxes. The Cepheids are used to calibrate an even brighter milepost marker that can be used over greater distances, a Type Ia supernova (SN1993id), which is circled in red.
galaxy to an unusually high accuracy of 3%. Knowing this distance allowed Riess and his team to calibrate the Cepheids, which they then used to determine the true luminosities of Type Ia supernovas in the other six galaxies.

Once the Type Ia supernova luminosities are calibrated via Cepheids in this way, they greatly extend the accuracy and utility of the cosmic distance ladder, as well as permit a significantly more accurate value of the Hubble constant to be obtained.

In 2009, the Riess team was able to measure the Hubble constant, $H_0$, to an accuracy 2.5 times greater than the previous 2001 Hubble result. In addition to the use of NGC 4258 as the “anchor galaxy,” astronomers needed Hubble’s powerful infrared capabilities with NICMOS for the study. Infrared light is key because it penetrates intervening dust that might interfere with the precise measurement of a Cepheid. This helped the team obtain more accurate measurements of the Cepheids’ true brightnesses, free from the obscuration that occurs from the dust.

Using Hubble as the only telescope for Cepheid observations was absolutely essential to the SH0ES team’s success. This eliminated the inevitable “systematic errors” that arise when data from different telescopes are taken and analyzed together. With Hubble, the team was able to sidestep some of the shakiest rungs along the previous distance ladder involving uncertainties in the behavior of Cepheids. At the current time, Hubble Space Telescope is the sole facility that can observe supernova explosions deeply enough and accurately enough to chart the early days of dark energy.

The Challenge Ahead

In the 400 years since Galileo turned his telescope to the sky, there have been just a few instances where observational astronomy challenged fundamental physics. The discovery that the universe is accelerating has handed this generation just such a challenge. It is both a shocking surprise and an exciting opportunity for theoretical and observational scientists alike.

The SH0ES team has made a more precise and accurate measure of the Hubble constant; which, together with the WMAP measurements in the early universe, has yielded a measurement of dark energy consistent with Einstein’s cosmological constant. Eventually, Riess envisions the Hubble constant being refined to a value with an error of no more than one percent, to put even tighter constraints on solutions to dark energy.
Dark Energy

UPDATE:
Already new observations from WFC3 have doubled the amount of data of the same type reported here. We anticipate improving the precision of the measurement significantly in the coming year.

Further Reading


Dr. Adam G. Riess is a professor of astronomy and physics at The Johns Hopkins University and a senior scientist at the Space Telescope Science Institute, both in Baltimore, Maryland. His research involves cosmological measurements and analysis. In 1998, he led a group study that provided the first direct and published evidence that the expansion of the universe was accelerating and filled with “dark energy.” Beginning in 2002, Dr. Riess led the team to find 25 of the most distant supernovas known with the Hubble Space Telescope. This work culminated in the highly significant first detection of the preceding decelerating epoch of the universe, helped to confirm the current acceleration, and began to characterize the time-dependent nature of dark energy. Dr. Riess has been awarded the Warner, Shaw, Gruber, and Sackler prizes for academic achievement, is the recipient of a MacArthur Fellowship, and was elected to the National Academy of Sciences in 2009. Dr. Riess earned his Ph.D. in Astrophysics from Harvard University.
The Institute’s website is: [http://www.stsci.edu](http://www.stsci.edu)
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JWST SWG (Redondo Beach) ......................... 9–10 March 2011
YAE Astronomy Club (STScI) ....................... 19 March 2011
http://www.stsci.edu/institute/conference/youthae
STUC (STScI) ........................................... 6–7 April 2011
AURA Board (Tucson) ................................. 13–16 April 2011
YAE Astronomy Club (STScI) ....................... 16 April 2011
http://www.stsci.edu/institute/conference/youthae
STScI May Symposium “Dark Matter” ............. 2–5 May 2011
http://www.stsci.edu/institute/conference/spring2011
TAC Meeting (STScI) ................................... 16–20 May 2011
AAS Meeting (Boston) .................................. 22–26 May 2011
JWST Advisory Council (STScI) .................... 1–2 June 2011
“Frontier Science Opportunities with JWST” ........ 6–8 June 2011
http://www.stsci.edu/institute/conference/jwst2011
STIC (STScI) ............................................. 9–10 June 2011
“Very Wide Field Surveys in the Light of Astro2010” . 13–16 June 2011
http://www.stsci.edu/institute/conference/verywidefield
C19 Results Announced ................................. mid-June 2011
Parent and Daughter Evening under the Stars (STScI) ... 4 November 2011
http://www.stsci.edu/institute/conference/youthae
Parent and Son Evening under the Stars (STScI) ........ 11 November 2011
http://www.stsci.edu/institute/conference/youthae