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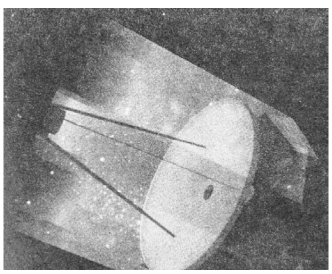
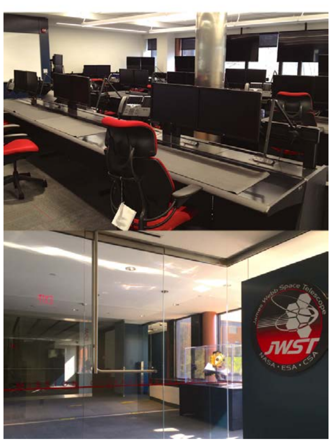
Search

NGST: The Early Days of *JWST*



Nearly 30 years ago Riccardo Giacconi, then the Institute Director, challenged Peter Stockman (Research Branch Head) and me (Deputy Director) to "think about the next major mission beyond *Hubble*." This was still several years before the launch of *Hubble*, during the period after the *Challenger* accident when the future looked unclear. Riccardo was concerned that major missions take a very long time between inception and commissioning, longer typically than the then-expected 15-year life for *Hubble*...

Preparing for the First *James Webb Space Telescope* Proposals

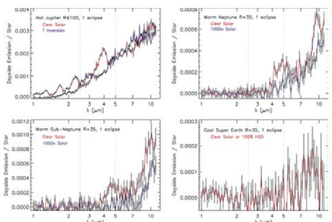


The integration and testing of the *James Webb Space Telescope* is on schedule for a nominal October 2018 launch, and recently its beautiful mirror assembly was revealed in the clean room. This means that we are now a year from the first open call for proposals for observing with *Webb*—namely the Early Release Science (ERS) program call—planned for May 2017...

Previews of the *James Webb Space Telescope*: The Frontier Fields Program

The Frontier Fields program is the latest chapter in *Hubble*'s hallowed tradition of deep-field initiatives. This time, by combining deep *Hubble* imaging with gravitational lensing, astronomers have observed the faintest sources ever studied, even fainter than those revealed in the Ultra-Deep Field...

Exploring New Worlds with *Webb*



Exoplanet researchers are counting down the days until the launch of the *James Webb Space Telescope*. *Webb* will transform our ability to unveil the atmospheres of planets transiting close to their parent stars. The community is in the process of developing tools, obtaining complementary observations, and planning for the first round of *Webb* observing proposals...

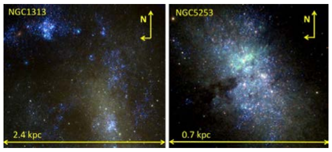
The *JWST* Advisory Committee (JSTAC): Maximizing the Scientific Productivity of *JWST*

The JSTAC's role, distilling its charge down to a key phrase, is to advise the Institute Director on "maximizing *JWST*'s scientific productivity" during its operational life. While this enunciation is simple and focused, the challenges during science operations for a mission of the complexity of *JWST* facing the partner agencies (NASA, ESA, and CSA) and the Institute, and an advisory committee like JSTAC, are similarly wide-ranging and complex...

State of the *Hubble* Observatory

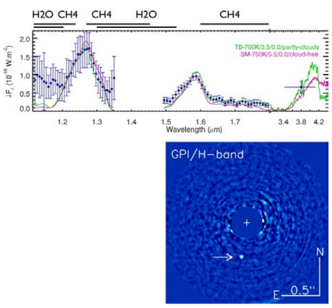
Now in its 26th year of operations, *Hubble* is still going strong, producing science that continues to challenge and expand our understanding of the universe. From predicting supernovae, to finding the most distant spectroscopically confirmed galaxy, to detecting water vapor plumes above the surface of Europa, the breadth of *Hubble*'s science is vast and continues to grow...

The Legacy ExtraGalactic UV Survey (LEGUS)



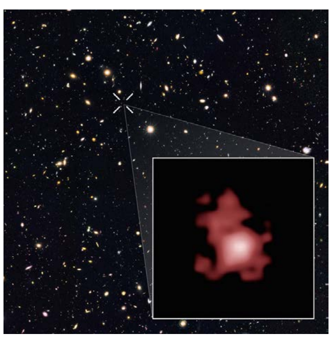
The combination of UV capability, high-angular resolution, and large field of view afforded by the *Hubble Space Telescope* is the foundation of the Legacy ExtraGalactic UV Survey (LEGUS), GO-13364...

New Science from Old Data: Finding Debris Disks in the *Hubble* Archive



The past 5–10 years have seen major breakthroughs in our knowledge of exoplanet populations. With more than 1600 exoplanets detected by the *Kepler* mission, we know that our solar system is not unique in the universe, and that planets are actually relatively common: Two sun-like stars out of three have a planet smaller than Neptune within 0.75 AU, while every dwarf M star— which are much more numerous than stars like our Sun—hosts at least two planets within similar orbits...

Hubble Extends Our Cosmic Horizon Back Through 97% of Cosmic History

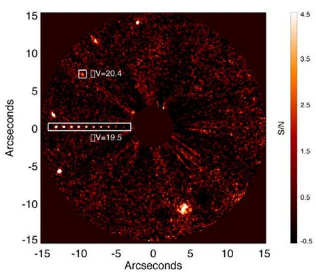


In *The Realm of Nebulae*, Edwin Hubble wrote: "The history of astronomy is a history of receding horizons," a quote which could not be more fitting to describe the story and the discoveries of the *Hubble Space Telescope*. During its 26 years in space, *Hubble* has steadily pushed our observational horizon to earlier and earlier cosmic times and transformed our view and understanding of how galaxies built up and evolved in the early universe...

Our Place in Space: *Hubble* Images and Inspired Art

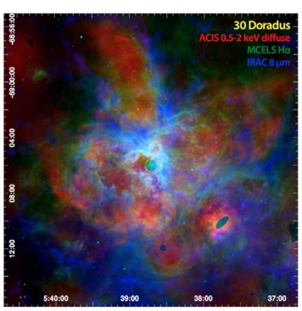
For more than two decades, *Hubble*'s images have engaged the public and bolstered interest in science and astronomy. Scientists and the public alike have been inspired by the fundamental questions that are often triggered by *Hubble* discoveries: Where do we come from? Where we are going? Are we alone? The new exhibit, *Our Place in Space*, is designed to capture the spirit of wonder and inspiration generated when we pause to ponder humanity's place in the grand scheme of the cosmos...

Pushing High-Contrast Imaging with *Hubble* to the Limits



In 1980, a paper by D. W. Davies pointed out that a 2.4-meter telescope like *Hubble* could reasonably expect to detect an exoplanet in reflected light—provided that one could integrate sufficiently long to overcome the overwhelming background caused by a host star's point spread function (PSF), the diffraction pattern of a telescope created by the shape of the primary mirror, the support structure/secondary mirror, and any pupil plane aberrations (Davies 1980)...

Workshop on *Feedback in the Magellanic Clouds*

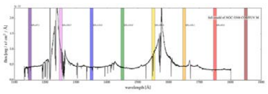


The Institute hosted a science workshop from October 5–7 2015 on *Feedback in the Magellanic Clouds*. This event focused on stellar and galactic feedback in two of our nearest dwarf-galaxy neighbors, the Large and Small Magellanic Clouds. It featured 75 registered participants, 32 posters, 13 invited talks, and a range of contributed talks and discussions...

Big Data Drives New Approaches to Doing Science

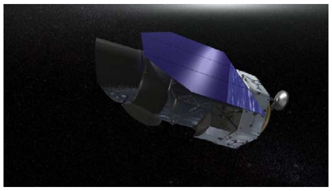
Big data is everywhere, and astronomy is no exception. Our ability as a society to measure ever more about consumers, take ever more pictures, and send ever more messages has been mirrored in our ability to acquire ever more digital information about the cosmos. Experiments of the next decade like Large Synoptic Survey Telescope and the Square Kilometer Array are slated to ingest an unprecedented volume of astronomical data...

The *Hubble* Spectroscopic Legacy Archive (HSLA)



Data archiving is a crucial component of the operation of an astronomical observatory. Archives ensure the legacy of the observatory, and act as multipliers for its science output, by enabling science investigations unrelated to those in the proposals that obtained the data...

Wide Field Infrared Survey Telescope (*WFIRST*) Starts Mission Formulation Phase



The Wide Field Infrared Survey Telescope (*WFIRST*) got its formal start in February 2016, when NASA advanced it into the mission Formulation Phase, with launch aimed for the mid 2020s. This marked the completion of several years of pre-formulation work, capped by a successful Mission Concept Review in December 2015...

AAS 228 June 2016, San Diego

The Space Telescope Science Institute will be at the 228th AAS meeting in San Diego, California, with an exhibit booth showcasing the missions we support for the science community, several technical presentations in instrument sessions, a wide variety of science presentations, and press releases. Come see what's new! ...

NGST: The Early Days of *JWST*

Search

Garth Illingworth, *gdi@ucolick.org*

Nearly thirty years ago Riccardo Giacconi, then the Institute Director, challenged Peter Stockman (Research Branch Head) and me (Deputy Director) to "think about the next major mission beyond *Hubble*." This was still several years before the launch of the *Hubble Space Telescope*, during the period after the *Challenger* accident when the future looked unclear. Riccardo was concerned that major missions take a very long time between inception and commissioning, longer typically than the then-expected 15-year life for *Hubble*. While I cannot remember the details of exactly when this took place, I can remember thinking that this was somewhat crazy given the work remaining on *Hubble*. But resisting Riccardo without well-formulated arguments was not likely to be successful—especially on this topic, given that Riccardo was one of the few people at that time to have done major space science missions.

Together with a very imaginative engineer, Pierre Bely, Peter and I took the challenge to grow the seed planted by Riccardo into a mission. Peter, Pierre, and I began to think about what might be a worthy scientific successor to *Hubble*. Fortunately, Pierre had already been working in 1986 on a game-changing approach for a large optical-IR telescope. This was passive cooling, which allowed structures shielded from solar heating to reach very low temperatures by radiating to space, thereby eliminating the huge thermal background. Angel, Cheng, and Wolff (1986) had also espoused a similar approach for a 16-m space telescope in their effort to find earth-like exoplanets. A paper led by Pierre (Bely et al. 1987) at the SPIE meeting in Los Angeles in January 1987 discussed a passively cooled 10-m telescope that would operate at ~130 K.

While the core of the group that led the development of the *Next Generation Space Telescope* (*NGST*) mission concept at that time was Pierre Bely, Peter Stockman and me, we were extremely lucky to have Riccardo's continuing support and encouragement, and an extraordinarily talented and imaginative group of engineers and scientists at the Institute—including James Crocker, Mark Rafal, and Chris Burrows—who worked with us on many aspects of the concept development.

Given the modest beginnings to this effort, it was striking that it rapidly gained in visibility and interest. I gave a talk at the 20th IAU in Baltimore in August of 1988 titled The Next Generation: An 8–16 m Space Telescope (Illingworth 1990). This talk discussed the progress on a concept for an 8-m filled-aperture, passively cooled, wide-band UV-Visible-IR telescope in high earth orbit and outlined its extraordinary science capabilities (e.g., distant galaxies; resolving nearby galaxies; earth-like planets). The 8–16-m telescope was endorsed in the 1988 study Space Science in the Twenty-First Century: Imperatives for the Decades 1995–2015 by the National Academies, and was one of the two long-term programs highlighted in the 1990 UV-Visible Management Operations Working Group Strategy Report.

The most important activity for the development of a mission concept, however, was a workshop that was held at STScI the following year, 13–15 September 1989. This workshop, organized as The Next Generation: A 10 m Class UV-Visible-IR Successor to *HST*, covered the scientific opportunities that would come from a cold, diffraction-limited UV-optical-IR 10-m space telescope, as well as the technological challenges that would arise for such an ambitious project. This workshop built on Pierre's 1987 paper and the work done by the group. Ed Weiler, the Chief of the Ultraviolet/Visible and Gravitational Astrophysics Division (and *Hubble* Program Scientist) at NASA HQ, agreed to support the workshop. We greatly appreciated Ed's support since the linkage with NASA was crucial in a development of this nature. A significant number of the participants were from NASA Centers (GSFC, JPL, MSFC), as well as from industry and NASA contractors, who also brought unique experience to the table. A collaboration with ESA, as was being done for *Hubble*, was also discussed. The scientific, technical, and political value of such international collaboration for very large projects was recognized (as noted in the "Sage Advice" by John Bahcall). The conference proceedings and discussion were published in 1990, edited by Bely, Burrows, and Illingworth, highlighting the joint sponsorship of NASA and STScI.

Just two months before the 1989 meeting, then President George H. W. Bush proposed a major lunar initiative. NASA asked us to include a potential lunar siting in the discussions. This was already of interest to some of the participants, and so we quickly put a 16-m lunar-based telescope into the baseline discussion. But for most participants the focus was on the 10-m *Next Generation Space Telescope*. The efforts on a lunar-based 16-m continued for a few years during President Bush's tenure, but died away in the early 1990s with the change of leadership and the financial challenges of the 1991–92 recession.

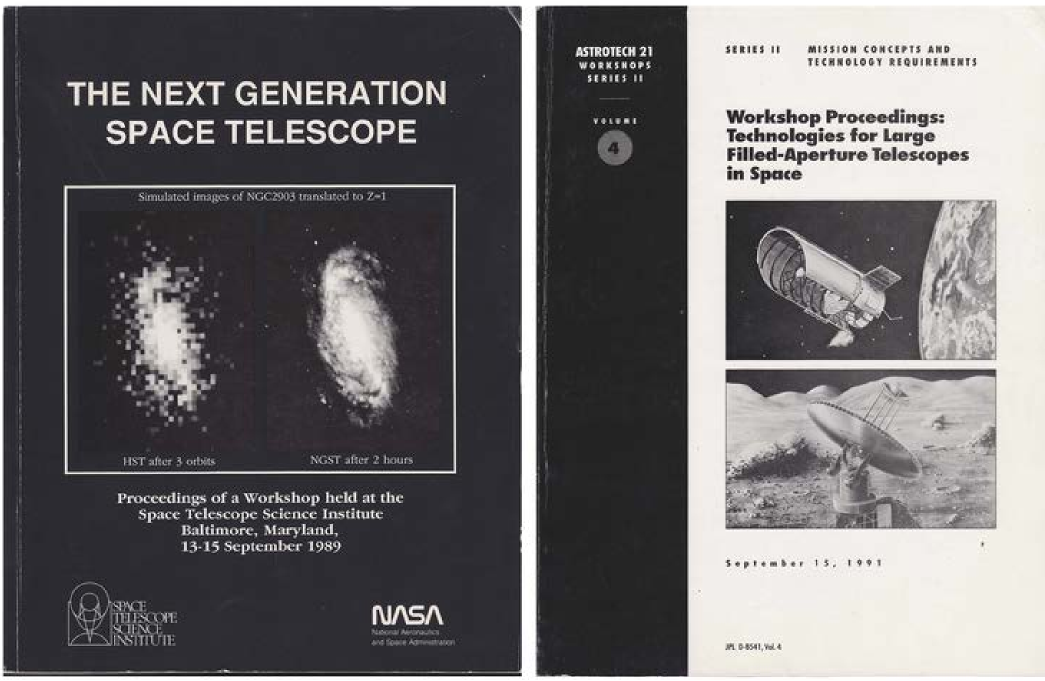


Figure 1: The *Next Generation Space Telescope* workshop in 1989 and the Astrotech 21 workshop in 1991. These, along with the work done for the UV-Optical in Space panel of the 1990 Decadal Survey, were some of the key activities in the early development of *NGST*.

A major step forward occurred with the UV-Optical in Space Panel of the 1990 Decadal Survey (led by John Bahcall). The Panel made a number of recommendations, of which one was for a 6-m cooled space telescope as a successor to *Hubble*. This was called the *Large Space Telescope* in the report. The Panel noted, "The scientific case for enhanced Observatory-class capability in the UV-IR region is overwhelming. The panel strongly recommends that a 6 m-class telescope be launched in the first decade of the next century." It was essentially the 10-m *NGST* that had been discussed in the 1989 STScI workshop scaled to 6 m (anything less was only a modest gain over *Hubble* and gave low resolution in the mid-IR).

The *NGST* team developed an estimate of the cost. The UV-O-IR 6-m concept presented to the panel was costed at $2B in 1990 dollars with a project start in 1998 and launch in 2009. Given other goals, the full Decadal committee did not accept the Panel recommendation. It is interesting to compare the 1990 Decadal *NGST* cost estimate of $2B with the $1B cost estimate in the 2000 Decadal Survey. Inflating the 1990 $2B estimate to 2000 dollars gives $2.6B. As events have shown, this would have been a better starting cost estimate for *NGST* in the 2000 Decadal, but given the political environment at that time such a figure could well have killed *NGST*/*JWST* before it got started.

While the Decadal Panel recommended 6 m, this size was not carried forward in subsequent discussions. The size of the high-earth-orbit *NGST* mission concept settled down to around 8 m in the early 1990s as the "sweet spot" for this mission. The issue of cost also framed much of the developments and discussions about technology over the next few years. Illingworth (1991) enunciated some of the reasons why *NGST* was expected to cost less than expected from that predicted from the *Hubble* cost-curve (e.g., over 20 years of technological development; weight that was comparable to or less than *Hubble*).

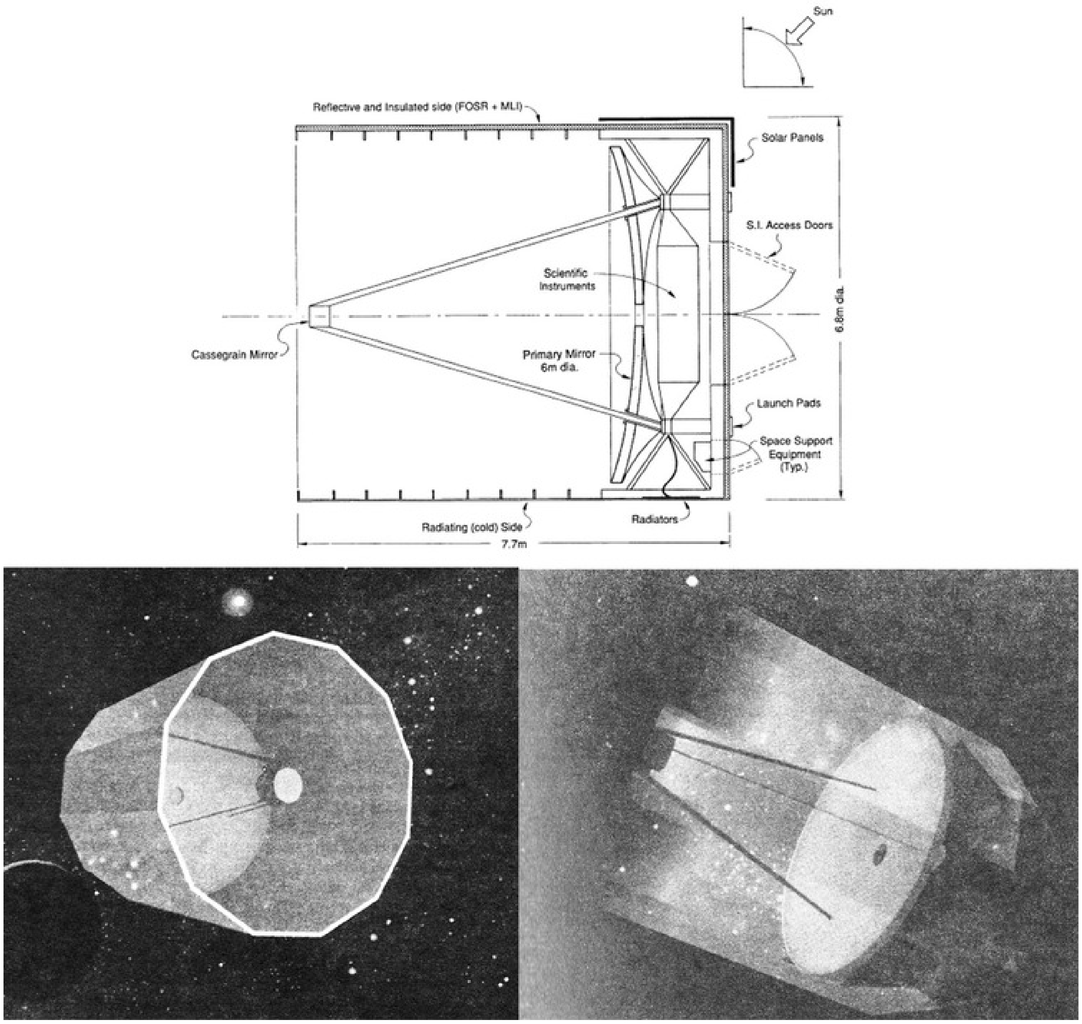


Figure 2: The *NGST* concept layout discussed by the UV-Optical in Space panel of the 1990 Decadal Survey, along with a couple of renditions. *JWST* looks very different from this early concept!

A key activity in 1989–1992 was the inclusion of *NGST* into the Astrotech 21 program that was implemented to identify needed technologies for future programs. This was a joint initiative from NASA HQ Astrophysics and the Advanced Technology program, with planning support from JPL. Key people in this initiative were Mike Kaplan, the Chief of the Advanced Programs Branch in Astrophysics at HQ, Max Nein at Marshall Space Flight Center, where many studies were carried out, and Jim Cutts, the Astrotech 21 manager at JPL.

There were a number of workshops organized under the Astrotech 21 program. The *NGST* workshop was organized by the Astrotech 21 office at JPL and was held in Pasadena March 4–5 1991 to develop recommendations and priorities for input to Astrotech 21. The mission concept workshops were designed to flow requirements down into workshops focused on needed technological capabilities. What was increasingly becoming clear was that *NGST*'s cold optics would become contaminated by outgassed material that would greatly impact the UV throughput. If *NGST* was to meet its IR objectives through cooling to 100 K or less, it would become extremely difficult to have UV capability (the challenges of building diffraction-limited optics in the UV were also a factor). The baseline for *NGST* became optical-IR. Around this time a concept that also used passive cooling, the 1.7-m Edison telescope, was proposed in Europe (but not selected, unfortunately).

A series of events then occurred that had a major impact on the funding and the development efforts for *NGST*—

the recession of 1991–1992, *HST*'s problems with spherical aberration, and the change of Administration. Little was done on *NGST* for several years. It was not until 1995 and 1996 that *NGST* activities resumed. They did so vigorously. A key step was taken when Ed Weiler had an opportunity to fund a modest development effort on *NGST* starting in the early fall of 1995. Ed enlisted John Mather and Bernie Seery at GSFC to lead a small team to advance the *NGST* mission concept, with the support of John Campbell, the *HST* Project Director, as well as Peter Stockman and Pierre Bely. John Mather is with *JWST* still as the Senior Project Scientist. Eric Smith, the current *JWST* Program Director at NASA HQ, also joined the activity early in 1996. This development effort was a crucial step in reinvigorating *NGST*.

The report of the AURA *HST* and Beyond study (Dressler 1996) was also moving towards completion at that time. This committee had been formed late in 1993 by AURA with Alan Dressler as Chair to begin a broad study of possible future missions for UVOIR astronomy. This large committee had a broad remit. Its report was published in May of 1996 after 2.5 years of substantial effort on a complex and multi-faceted topic. One of their recommendations was that "NASA should develop a space observatory of aperture 4 m or larger, optimized for imaging and spectroscopy over the wavelength range 1–5 µm."

The endorsement of the *NGST* approach was appreciated, but those who had worked on *NGST* for many years saw the 4 m as a rather incremental step over the 2.4-m *Hubble*. Fortunately, in his talk at the January 1996 AAS meeting, then NASA Administrator Dan Goldin expanded the *HST* and Beyond recommendation to a larger telescope with "I see Alan Dressler here. All he wants is a four-meter optic that goes from a half micron to 20 microns. And I said to him, 'Why do you ask for such a modest thing? Why not go after six or seven meters?'" Subsequently, 8 m actually became Dan Goldin's preferred size for *NGST*.

NGST had entered a new era. With support from Ed Weiler, who was then the Origins Theme Director at NASA HQ, several concept studies were initiated, fortunately at the 6–8-m level. The publication of these studies into a single volume edited by Peter Stockman (Stockman 1997) marked a key step that set *NGST* on a path to a fully-fledged mission. The story of that time remains for a future article, but the NASA start occurred when the Office of Space Science AA Ed Weiler signed the Formulation Authorization on March 8, 1999, followed by the first-ranked recommendation for an 8-m *NGST* by the 2000 Decadal Survey committee. *NGST* was re-scaled to 6.5 m in early 2001, and the name changed from *NGST* to *JWST* in September 2002.

This is clearly a short vignette of a remarkable period when much was done that set *NGST* onto the path that led to *JWST*. An excellent and comprehensive discussion can be found in Chapter 2 of the 2007 workshop Astrophysics in the Next Decade (Smith & McCray 2009; including a detailed list of references). *NGST* arose from a team effort that involved numerous imaginative and enthusiastic scientists, engineers and managers from across NASA, industry and academia.[1]

Yet all such efforts begin somewhere—30 years ago it was the challenge that Riccardo Giacconi made to us (Peter, Pierre and me) at the Institute to "think about the next mission" that set *NGST* on a path to *JWST*, now just a couple of years away from launch.

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Stockman, P. (Ed.) 1997, *The Next Generation Space Telescope. Visiting a Time when Galaxies Were Young (Baltimore, MD: STScI and Washington, DC: AURA)*

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[1] Many of those involved are named here, but many could not be listed because of space limitations. I apologize for any omissions. The development of *NGST* will certainly be the subject of more extensive and thorough expositions in the future.

Preparing for the First *James Webb Space Telescope* Proposals

Klaus Pontoppidan,[1] *pontoppi@stsci.edu*

The integration and testing of the *James Webb Space Telescope* is on schedule for a nominal October 2018 launch, and recently its beautiful mirror assembly was revealed in the clean room at NASA's Goddard Space Flight Center (GSFC). This means that we are now a year from the first open call for proposals for observing with *Webb*—namely the Early Release Science (ERS) program call—planned for May 2017. The ERS is a program awarding approximately 500 hours of observing time early in *Webb* Cycle 1 to exciting science programs for immediate release to the astronomical community. Following this, a call for the full Cycle 1 General Observer program will be issued in November 2017.

Anyone responding to these opportunities will have the use of a comprehensive set of planning tools. The first flight-ready systems to be made available include the Astronomer's Proposal Tool (APT), the Exposure Time Calculator (ETC), various simulators and other helper tools, as well as a wide-ranging user documentation system. In spring 2017, all tools necessary for planning science observations for Cycle 1 will be released. We are excited to see the hard work that has gone into developing the *Webb* ground system over the past years now come to fruition, as all the planning tools are being polished in preparation for *Webb* science.

How do I observe with *Webb*? The new *Webb* documentation system

The user documentation for *Webb* is under active development, and it will look quite different from *Hubble*'s documentation. The system, informally called JDOX, uses a Wikipedia-like format, in which a large number of topical, self-contained, and hyperlinked articles are available on a fully online repository.

Figure 1: Screenshot from the new *Webb* documentation system.

The information is organized following the "Every Page is Page One" style.[2] EPPO is a system designed specifically for technical documentation where typical users are searching for specific pieces of information, rather than reading a comprehensive handbook front-to-back. JDOX will release articles incrementally, as they become available, starting with information needed for proposal planning, such as background articles for every instrument, followed by proposal planning articles. Data processing and analysis articles will follow later. The first JDOX release is planned for early summer 2016.

Along with the documentation release, we have published a new *Webb* website, which contains more information about the proposal process, links to the various tools and news items.[3]

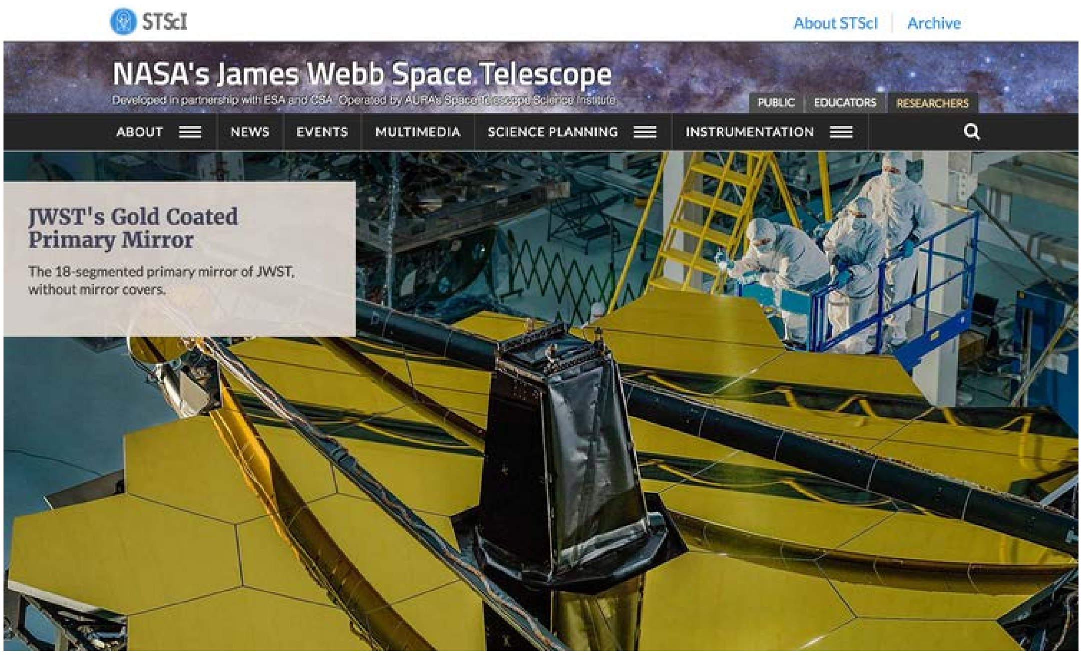

Figure 2: The new *Webb* website at the Institute.

Scripting *Webb*: The first operational builds of the *Webb* Proposal Tool

The Proposal and Planning System (PPS) “build 13” was completed in April, and will be undergoing testing in the next months. This is the build that supports commissioning and the target selection for Guaranteed Time Observations (GTOs). The next build (14) is the flight build supporting the GO Cycle 1 call for proposals, and is due for delivery to integration and testing in the fall of 2016. The formal release of the APT flight build for *Webb* is slated for spring 2017, although preliminary versions are already available for download. APT now includes an intelligent model for estimating overheads (called “smart accounting”), which takes into account how close visits within a given program are distributed on the sky to appropriately charge users with the actual slew time needed to execute their programs. A new visibility tool has also been developed for *Webb*, which graphically displays the time windows within which a given visit can be scheduled.

What’s the performance? Release of the *Webb* ETC

The Exposure Time Calculator (ETC) development team reached a major milestone in March, as the implementation of all the *Webb* science modes was completed. The *Webb* ETC, informally called “Pandeia,” is a new general Exposure Time Calculator tool and simulator, which models an observatory and instrument package by constructing full three-dimensional astronomical scenes and “observes” them with a model instrument, producing two-dimensional detector-plane products and methods for extracting signals, such as spectra or photometry. Pandeia consists of a Python engine, which calculates sensitivities, and a web application, which provides a powerful user interface for using the ETC. The *Webb* ETC is currently undergoing quantitative verification and testing. The full web application is due to be released in January 2017. To give the community access to *Webb* sensitivity calculations as soon as possible, a beta version of the engine will be released in May 2016 as an installable Python package. The ETC engine also allows for scripting and extensive parameter studies.

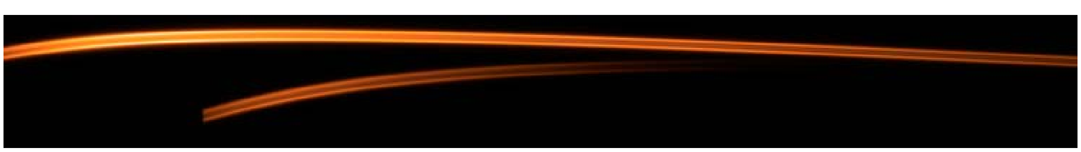

Figure 3: *Webb* ETC calculation for the NIRISS Single-Object Slitless Spectroscopy (SOSS) mode, showing two orders of the same source.

When the Exposure Time Calculator is not enough

There are aspects of planning for *Webb* science where more advanced simulations than basic ETC calculations are needed, so several simulators are being prepared for general release. STIPS is the simulator for the *Webb* imaging modes with NIRCam and MIRI. It calculates full-field simulated data products for populations of stars and galaxies. An exoplanet transit observation simulator for the community, using the *Webb* ETC engine, is under development by Natasha Batalha (Penn State University), and will also be accessed through a web application.

Webb update: Assembling a spacecraft

The *Webb* integration and testing reached several major milestones this spring. The final instrument-level cryogenic vacuum test (CV3) was completed at NASA's Goddard Space Flight Center (GSFC), and a comprehensive analysis of the data obtained during the test is underway. Overall, the observatory is healthy and the CV3 test is considered a great success. The assembly of the optical telescope was completed (including the installation of all primary mirror segments, the secondary and the aft optics). Keep a close eye on the GSFC cleanroom webcam in the next few months to see the telescope with the dust covers taken off in preparation for various tests! The next major step is the integration of the instrument module (ISIM) into the optical telescope (OTE), forming the combined Optical Telescope Element and Integrated Science (OTIS), which is due to be tested at NASA's Johnson Space Flight Center (JSC) in 2017.

The construction of the Mission Operations Center (MOC) at the Institute was completed, and it is ready for use training flight operations personnel. In flight, *Webb* will be operated from the MOC, and telemetry from the spacecraft will arrive there via the Deep Space Network.

Figure 4: The *Webb* Mission Operations Center at the Institute.

[1] *James Webb Space Telescope* Deputy Project Scientist, Space Telescope Science Institute
[2] **http://www.everypageispageone.com**
[3] **http://www.stsci.edu/jwst**

Abell 370. Credit: NASA, ESA, J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI).

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Previews of the *James Webb Space Telescope*: The Frontier Fields Program

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Summary

The Frontier Fields program is the latest chapter in *Hubble*'s hallowed tradition of deep-field initiatives. This time, by combining deep *Hubble* imaging with gravitational lensing, astronomers have observed the faintest sources ever studied, even fainter than those revealed in the Ultra-Deep Field. This three-year Director's Discretionary program began in October 2013 and will conclude this coming September. Deep optical and near-infrared imaging of six galaxy clusters and six blank fields with both *Hubble* and *Spitzer* is almost complete. Supporting data have also been obtained with *Chandra*, Subaru, VLT, and other observatories. To date, over 60 papers have studied the observed clusters, supernovae, and distant galaxies out to $z \sim 10$, within the universe's first 500 Myr. The ultra-faint objects revealed in the Frontier Fields are giving us a preview of the universe we will observe with the *James Webb Space Telescope*.

The Frontier Fields program was described in previous *Newsletter* articles (Lotz et al. 2013; Ogaz et al. 2015). More details may be found via **http://www.stsci.edu/hst/campaigns/frontier-fields/**. Meetings to discuss the Frontier Fields have been organized in **Yale** and **Honolulu**. Here we provide an update on some of the science results to date, focusing on searches for distant galaxies.

Bold *Hubble* Deep Fields

The original *Hubble* Deep Field North (HDF-N) was a bold undertaking by the second Institute director, Bob Williams. It was unclear we would learn much by staring at a blank patch of sky for 10 days. But in 1995, those deep images revealed about 3,000 galaxies, including distant galaxies that were clearly very different from the galaxies we see around us today.

After the success of the HDF-N, *Hubble* followed with the HDF-S, and then the Ultra-Deep Field (UDF) in ultraviolet, optical, and infrared wavelengths. Each deep image of a blank patch of sky with successively upgraded cameras (WFPC2, NICMOS, ACS, and WFC3) yielded more insights into fainter and more distant galaxies.

However in 2012, with no further servicing missions planned to upgrade *Hubble*, it was unclear how best to improve on these deep-field programs. Significantly deeper imaging would be prohibitive, requiring too much telescope time. But additional UDFs (similarly deep) would be very useful to increase statistics and overcome cosmic variance.

Then-Institute Director Matt Mountain solicited ideas from the community and convened a committee to deliberate over them. One idea was gravitational lensing. The Cluster Lensing And Supernova survey with *Hubble* (CLASH; Postman et al. 2012) had recently delivered a candidate for the most distant galaxy known at $z \sim 11$, observed 420 Myr after the Big Bang (Coe et al. 2013). This distant galaxy is extremely compact, with a half-light radius less than 100 pc, or roughly the size of giant molecular clouds—star-forming regions in our universe today.

Much deeper imaging of galaxy clusters could reveal lensed populations of dwarf galaxies that were smaller and fainter than any observed before. These dwarf galaxies were likely the dominant source of reionizing flux in the early universe. They were also the building blocks of modern-day galaxies, including our Milky Way. Understanding these distant dwarf galaxies is the frontier of extragalactic research.

Ultimately, the unanimous recommendation from the *Hubble* Deep-Fields Initiative Science Working Group was the Frontier Fields. Six additional blank deep fields would be observed in parallel with six deep galaxy cluster observations (Figure 1). The directors of both *Hubble* and *Spitzer* (Matt Mountain and Tom Soifer) dedicated significant Director's Discretionary observing time to this program: 840 orbits and 1,000 hours, respectively. With 70 ACS orbits and 70 WFC3/IR orbits per cluster, the infrared *Hubble* imaging is 10 times deeper than any prior cluster-lensing WFC3/IR images.

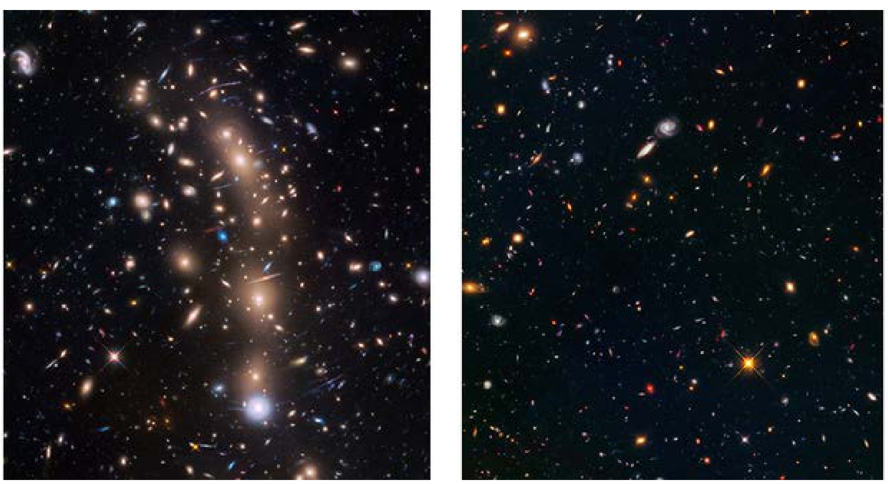

Figure 1: MACS J0416.1-2403 and its blank parallel field 6' away. Six pairs of fields like this are being observed by the Frontier Fields program. Credit: NASA, ESA, J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI).

This is a bold new direction for the *Hubble* deep-field programs. Staring deeply at massive galaxy clusters represents a significant departure from previous deep-field observations of blank patches of sky. Would ultra-faint distant galaxies get lost in the glare of the foreground galaxy clusters? Would lens-modeling uncertainties hinder any of our science goals?

Faintest Galaxies yet Known

Detecting the intrinsically faintest high-redshift galaxies is challenging. The intrinsically faintest galaxies are those that are highly magnified, yet still just faintly detected. Highly magnified galaxy images sometimes appear close to brighter galaxies in the lensing cluster, but modeling and subtracting these foreground cluster galaxies have revealed distant galaxies fainter than any previously observed.

Without the aid of gravitational lensing, the blank parallel Frontier Fields reveal galaxies as faint as 29th magnitude AB (5-sigma detections). This is roughly one magnitude shallower than the UDF (AB mag 30). However, the lensing power of the Frontier Fields clusters boosts the depth of those images by at least three magnitudes to AB mag 32 within small, highly magnified regions. This roughly matches the expected depth of ultra-deep *Webb* images of blank fields, incredibly giving us a sneak preview of *Webb*'s universe!

The Frontier Fields data show that z ~ 6–8 luminosity functions remain relatively steep all the way down to AB mag 32 (Figure 2; Atek et al. 2015; Livermore et al. 2016). This confirms there will be plenty of faint galaxies for *Webb* to observe at these redshifts. The Frontier Fields have also revealed galaxies among the most distant yet known at z ~ 10, in the first 500 Myr (Figure 3). One of these z ~ 10 candidates is lensed to form three multiple magnified images (Zitrin et al. 2014). Another is the faintest z ~ 10 candidate yet known, intrinsically about AB mag 32, magnified by a factor of ~20 to AB mag 28.5 (Infante et al. 2015). This dwarf galaxy (dubbed "Tayna") is about the size of the LMC, with a star-formation rate 10 times higher. These galaxies will be prime targets for detailed follow-up study with *Webb*.

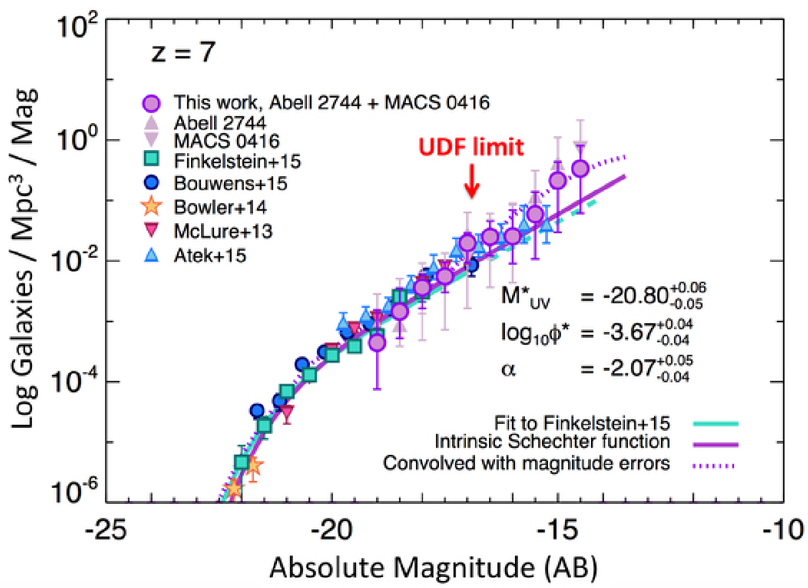

Figure 2: The z ~ 7 luminosity function (galaxies observed 750 Myr after the Big Bang) constrained ten times (2.5 magnitudes) fainter than the UDF, based on Frontier Fields imaging of the first two clusters (Livermore et al. 2016). The Frontier Fields images are revealing the faintest galaxies yet known.

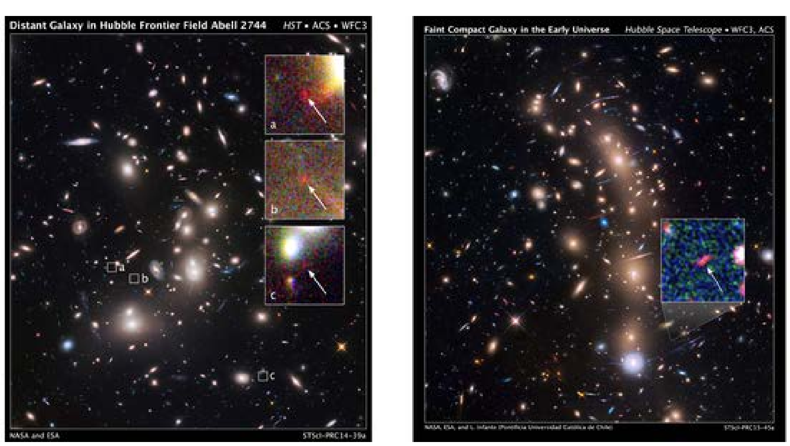

Figure 3: Candidate z 10 galaxies revealed by the Frontier Fields. Left: three magnified images of a z 10 candidate galaxy strongly lensed by Abell 2744 (Zitrin et al. 2014). Right: The faintest z 10 candidate known, magnified by a factor of 20 by MACS J0416.1-2403 (Infante et al. 2015).

One key unresolved question is whether the numbers of $z > 9$ candidates are consistent with expectations. Previous *Hubble* programs suggested a deficit of $z \sim 9$–11 galaxies compared to extrapolations from lower redshifts $z \sim 4$–8 (e.g., Oesch et al. 2013). This suggests that galaxies formed and evolved extremely rapidly in the first 500 Myr. Data from the Frontier Fields should strongly confirm or refute this claim (Coe et al. 2015). Based on the data obtained so far, some authors report confirmation of this rapid evolution (Laporte et al. 2016), while others have reported a less rapid, smoother evolution (McLeod et al. 2016). Further scrutiny of the full Frontier Fields dataset will be required to resolve this issue.

Lens Models Validated by Supernovae

Studying the properties of these lensed galaxies requires accurate magnification estimates. Lensing does not affect galaxy colors or any properties derived from them, such as redshift, age, or metallicity, but lensing uncertainties do propagate directly to estimates of galaxy mass, size, and star-formation rate.

Fortunately, the Frontier Fields clusters have the best lens models ever produced. The Institute initially coordinated the efforts of five teams as they shared the best available observational constraints and then delivered lens models of all six clusters to the community. (See the *Newsletter* article by Priyamvada Natarajan in Vol. 32, Issue 1.) These “version 1” models were made publicly available before the deep imaging began. Now based on the deeper Frontier Fields imaging and additional spectroscopy, improved models are being produced and delivered to the community. Figure 4 shows the improvement in strong lensing constraints for one cluster, MACS J0416.1-2403.

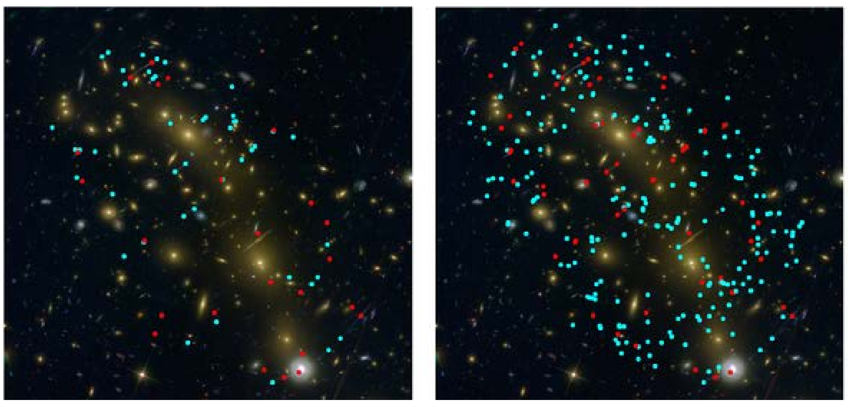

Figure 4: Lens models of the Frontier Fields clusters are the best ever produced, thanks to the exquisite data and collaborative modeling efforts. *Left:* Multiple images of galaxies lensed by MACS J0416.1-2403, as identified in CLASH imaging (Zitrin et al. 2013; Johnson et al. 2014). *Right:* Multiple images identified in deeper Frontier Fields imaging (Jauzac et al. 2014; Diego et al. 2015; Kawamata et al. 2016). Red circles indicate galaxies with spectroscopic redshifts, primarily from VLT X-Shooter (Christensen et al. 2012), CLASH-VLT (Grillo et al. 2015), and *HST* GLASS (Hoag et al. 2016).

Supernovae are providing direct empirical tests of the lens model accuracies. Lensed by Abell 2744, supernova Tomas is a Type Ia at $z = 1.3457$ (Rodney et al. 2015). This “standard candle” is observed to be about twice as bright as other Type Ia’s at similar redshifts. Lens model predictions for the magnification ranged from about two to three; on average, they were high by about 25%. This level of accuracy is roughly consistent with results from tests being performed on simulated data to quantify lens-model accuracies in more detail (Meneghetti et al., in prep.).

In November 2014, supernova Refsdal was lensed to form four multiple images by a cluster galaxy in MACS J1149.5+2223 (Figure 5; Kelly et al. 2015). The lens models predicted the supernova would reappear a year later in a fifth multiple image. Based on these predictions, astronomers proposed additional *Hubble* imaging to monitor Refsdal. The proposal was approved, and in December 2015, Refsdal reappeared right on schedule—as predicted by the lens models (Kelly et al. 2016).

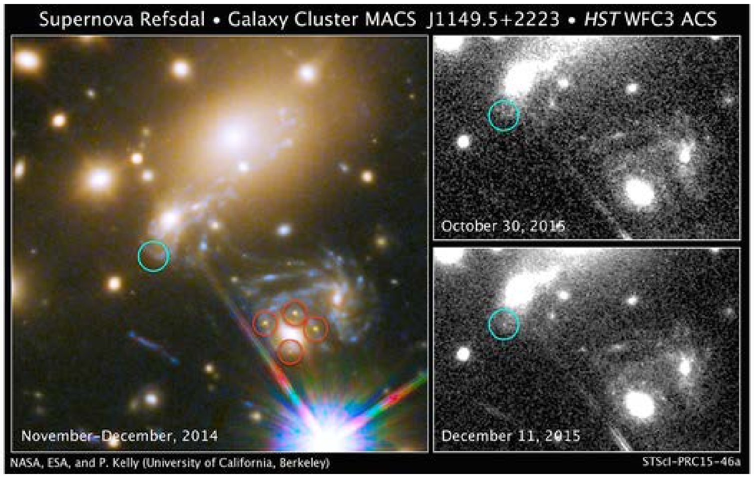

Figure 5: Refsdal is the first-ever-predicted supernova image. It appeared first as four multiple images in the red circles (Kelly et al. 2015) and then one year later in the cyan circle, as predicted by the lensing models (Kelly et al. 2016).

Frontier Fields Finale

The Frontier Fields *Hubble* and *Spitzer* imaging is nearly complete. All that remains is the deep *Hubble* ACS imaging of the final two blank fields, and deep WFC3/IR imaging of the final two clusters: Abell S1063 and Abell 370.

Abell 370 has historical significance. The long, bright, colorful arc (Figure 6) was the first to be confidently identified as a gravitationally lensed galaxy (Soucail et al. 1988). A new field of research was born. *Hubble* has since imaged Abell 370 multiple times with WFPC2, ACS, and WFC3. The deeper Frontier Fields ACS imaging was completed in February and can be seen in Figure 6 alongside the earlier ground-based imaging. This September, the deep WFC3/IR imaging will be completed, and the cluster that started it all will be the final Frontier Field.

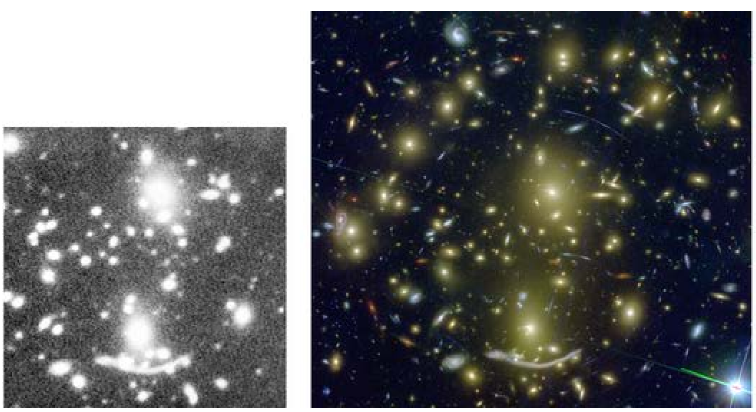

Figure 6: Abell 370, as observed in 1985 by CFHT (*left*) and today by *Hubble* (*right*). *Left:* The long arc at the bottom of this image was the first to be confidently identified as a gravitationally lensed galaxy (Soucail et al. 1988; image from Lynds & Petrosian 1989). *Right:* Deep ACS Frontier Fields imaging and shallow archival WFC3/IR imaging. Much deeper WFC3/IR imaging upcoming in July through September will conclude the Frontier Fields program.

We expect *Webb* to revisit the Frontier Fields; we selected the targets with that in mind. The *Hubble* images confirm an abundance of ultra-faint distant galaxies for *Webb* to examine in more detail. How many galaxies will *Webb* find within the first 400 Myr ($z > 11$)? Or the first 200 Myr ($z > 18$)? What will they look like? If the relative abundance of faint galaxies continues to climb with redshift, then the power of gravitational lensing will be further magnified. Lensing may prove to be the key to seeing the first galaxies with Webb.

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Credits/Contacts/Updates**http://www.stsci.edu/hst/campaigns/frontier-fields/Contact**

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Exploring New Worlds with *Webb*

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Exoplanet researchers are counting down the days until the launch of the *James Webb Space Telescope*. *Webb* will transform our ability to unveil the atmospheres of planets transiting close to their parent stars. The community is in the process of developing tools, obtaining complementary observations, and planning for the first round of *Webb* observing proposals.

Transit spectroscopy and *Webb*

Transiting exoplanets provide an excellent opportunity to study atmospheres in the most extreme conditions. When a planet passes in front of its star, some starlight is filtered through the upper regions of the planet's atmosphere. Tiny (1:10,000–1:1,000,000) fluctuations in the transit depth correspond to the signatures of absorbers in the planet's atmosphere.

The measurement of these miniscule signals requires low noise and well-characterized detectors and optics. *Webb* may not have been designed in the era of transit spectroscopy, but much instrumental testing has taken place with this type of observation in mind (e.g., Ferruit et al. 2014; Greene et al. 2007; Lagage et al. 2010). Starting exoplanet observing programs with the best possible knowledge of instrument behavior will help researchers prepare ahead of time for instrumental challenges. Feasibility studies to examine the likely recoverable information from *Webb* spectra are also being performed (Barstow et al. 2015; Greene et al. 2016; Figure 1).

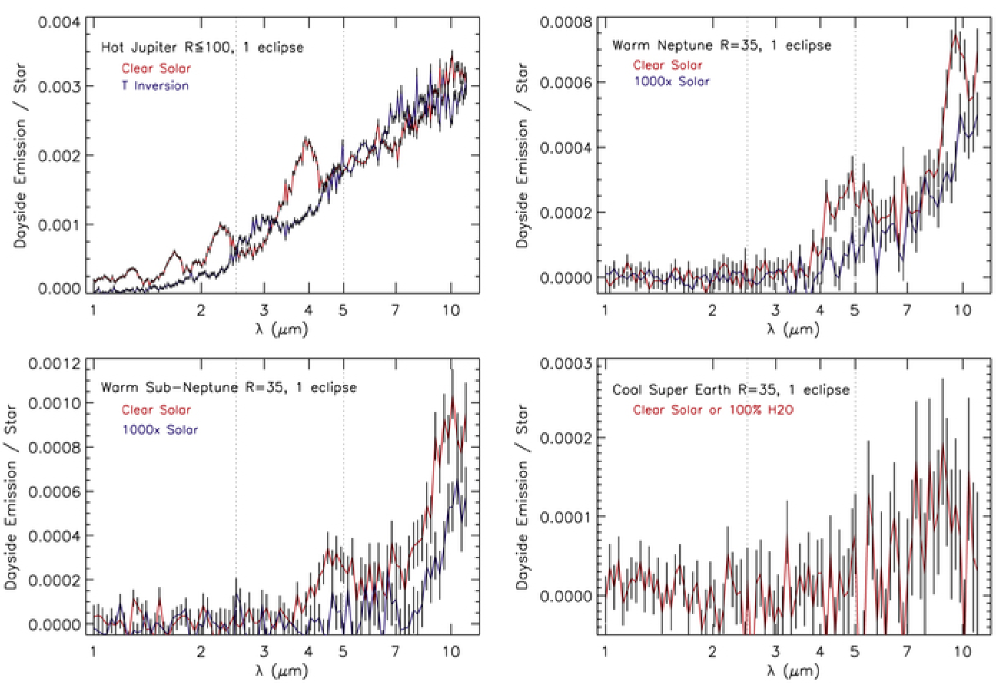

Figure 1: Simulated eclipse spectra taken from Greene et al. 2016. The spectra are for a single transit with equal time on the star alone for each of the four instruments. Spectra have been binned to resolution R ≤ 100 (hot Jupiter, warm Neptune, warm sub-Neptune) and R = 35 (cool super-Earth). The simulated spectra include a noise instance and presented as colored curves. The black error bars denote 1σ of noise composed of random and systematic components. Dashed lines show the wavelength range boundaries of the chosen NIRISS, NIRCam, and MIRI instrument modes. This figure was originally presented as Figure 5 of Greene et al. 2016, Characterizing Transiting Exoplanet Atmospheres with JWST, ApJ, 817:17, January 20, 2016. DOI: 10.3847/0004-637X/817/1/17. ©AAS. Reproduced with permission.

Remote sensing and degeneracy

Remote sensing is the process of inferring properties of atmospheres from images and spectra, obtained by telescopes and spacecraft. The information contained in these data is insufficient to fully specify the detailed properties of a planet's atmosphere. Retrieval techniques based on, for example, optimal estimation algorithms (Irwin et al. 2008; Lee et al. 2012; Rodgers 2000) or Monte Carlo (e.g., Madhusudhan & Seager 2009; Benneke & Seager 2012; Line et al. 2013; Waldmann et al. 2014), are used to infer the most likely state of the atmosphere from the limited information available.

Retrieval is challenging; often, multiple model solutions can be found that produce an equally good match to the data—a problem called degeneracy. For solar system planets that have been visited by in-situ probes, we can include an informed prior in the retrieval that restricts the range of possible solutions. For exoplanets, we don't have that luxury.

Webb's broad wavelength coverage (0.6–28 μm) will go some way towards solving the problem. For transit spectra, one of the biggest challenges is presented by the presence of clouds that obscure atmospheric absorption features due to gases and prevent us from seeing deep into the atmosphere (e.g., Kreidberg et al. 2014). But cloud opacity is often a strong function of wavelength, so using a broad wavelength range may help us to avoid this pitfall (Figure 2). When planets are viewed in eclipse, different wavelengths are sensitive to radiation emerging from different levels in the atmosphere, so a broad wavelength range means information about atmospheric structure over the greatest possible pressure range (Figure 3).

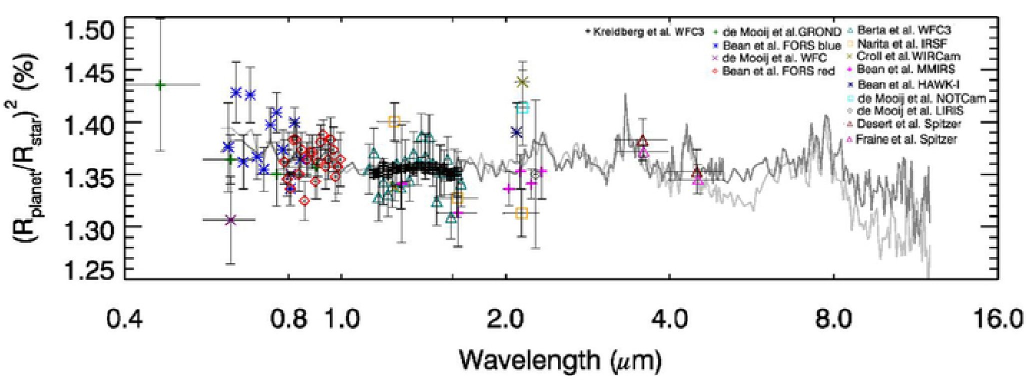

Figure 2: Simulated *Webb* primary transit spectra based on two different atmospheric models for cloudy super Earth GJ 1214 b (15 transits). Both are compatible with current data, but they diverge at wavelengths that will be sampled for the first time with *Webb*. Existing data are as shown in Barstow et al. (2013b), with the data from Kreidberg et al. (2014) and Fraine et al. (2013) added. The dark/light gray lines show models with the cloud top at 0.1/0.01 mbar. This figure was originally presented as Figure 16 of Barstow et al. 2015, Transit Spectroscopy with *JWST*: Systematics, Starspots and Stitching, MNRAS, 458, 2657.

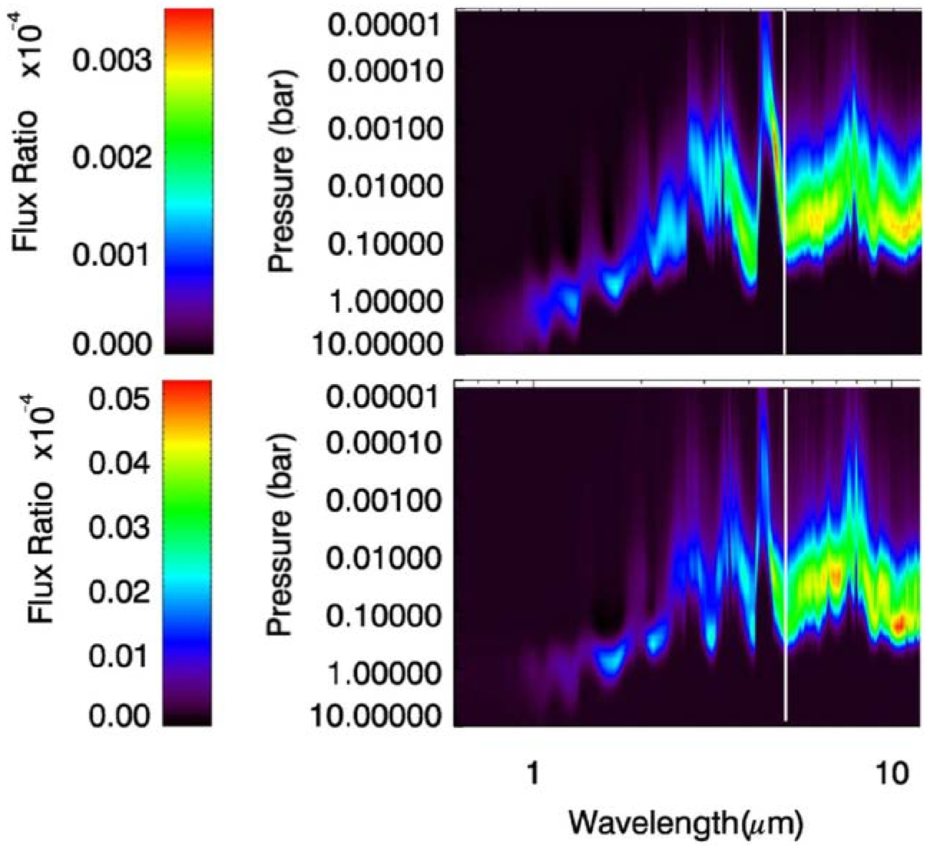

Figure 3: Retrieval sensitivity to temperature as a function of pressure and wavelength, for a hot Jupiter orbiting a Sun-like star (top) and a hot Neptune orbiting an M dwarf (bottom), as observed by *Webb* NIRSpec and MIRI instruments. The contours correspond to a change in observed flux ratio for a 1 K change in the temperature at each level in the atmosphere. The division between the NIRSpec and MIRI instruments is marked as a thin white line. This figure was originally presented as Figure 1 of Barstow et al. 2015, Transit Spectroscopy with *JWST*: Systematics, Starspots and Stitching, MNRAS, 458, 2657.

Another way of overcoming degeneracy is to exploit the range of different geometries available for transiting exoplanets. In transit, we observe starlight passing through the terminator atmosphere (the region between day and night) on a long path tangential to the planet's surface (Figure 4). These measurements are sensitive to the presence of high clouds and absorption by specific gases, but relatively unaffected by the atmospheric temperature structure.

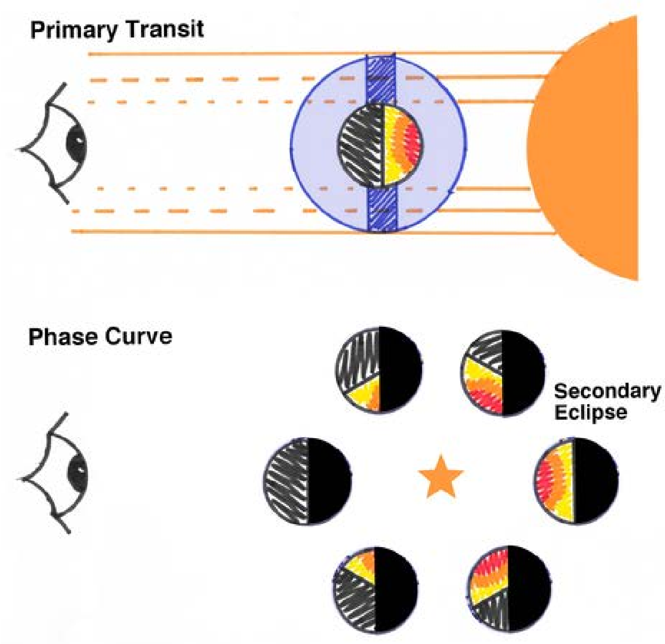

Figure 4: The various transit observation geometries. In primary transit, the signal of interest is from the starlight passing through the planet's atmosphere, whereas for secondary eclipse and phase curve measurements the signal is thermal radiation from the planet itself, emerging from the planet at different phases.

Secondary eclipse spectra probe thermal emission from the planet itself and penetrate deeper into the atmosphere. The temperature structure is encoded in these spectra, as well as absorption by gases. Secondary eclipse spectra at shorter *Webb* wavelengths will also contain contributions from reflected starlight, providing further information about the presence and scattering properties of clouds. Eclipse spectra probe the starlit (dayside) part of the atmosphere.

For key targets, it's possible to observe flux from the planet at a range of angles. By observing the system for the duration of the planet's orbit, monitoring the slight change in flux tells us about the varying contribution from the planet as our view changes from one of the hot dayside to the cooler, fainter nightside. This kind of measurement allows us to make a longitudinal map of the planet's properties (e.g., Stevenson et al. 2014), which can be compared with circulation models that predict wind speeds and structure (e.g., Kataria et al. 2015).

Although these different measurements probe different regions of the atmosphere, we anticipate that the sensitivity to different parameters can be exploited to break degeneracies. Additionally, measurements made by alternative techniques using ground-based telescopes (e.g., high resolution Doppler spectroscopy, Snellen et al. 2010) can provide necessary prior information.

Preparing for *Webb*

Currently, efforts are focused on preparing for the *Webb* Early Release Science (ERS) program. This community-selected program will execute early in Cycle 1, with the goal of producing scientifically compelling data sets in all of the major modes of *JWST* available to the broad community with no proprietary time. The ERS program will provide proposers from Cycle 2 onwards with information about instrument performance in scientific observations. The exoplanet community is at work identifying suitable targets that can be observed with a range of instrument modes during ERS, to provide maximum information about the telescope's performance for transit spectroscopy (Stevenson et al. 2016). In preparation, *Hubble* will likely perform reconnaissance of these targets. More information on the ERS program is available on the Institute's website, **https://jwst.stsci.edu/science-planning/early-release-science-program**.

In addition, efforts are underway to acquire UV and optical spectra of likely *Webb* exoplanet candidates while *Hubble* is still operational, since this wavelength region is critical for studies of clouds in both transit and eclipse. With these legacy spectra and new observations with *Webb*, we hope to extend studies such as that presented by Sing et al. (2016) to a much wider range of objects.

Towards terrestrial planets?

Webb will be a fantastic tool for comparative spectroscopy of hot Jupiters and warm Neptunes, but what about the more challenging smaller, temperate planets? With *Webb*, it may be possible to detect evidence of biosignatures such as ozone on an Earth-like planet orbiting in the habitable zone of a nearby cool M dwarf (Barstow et al. 2016). One such system, with three planets orbiting the M8 star TRAPPIST-1, has recently been discovered (Gillon et al. 2016). However, such a measurement would require observation of at least 60 transit events, taking up a significant proportion of the available observing time (Barstow et al. 2016). The decision of whether to pursue such a program would be a difficult one. The science return could be enormous, but the risk is high that biosignatures could be absent or obscured by clouds.

It is likely that *Webb* will be pushed to the limit of its capabilities for new exoplanet science. Whether or not that is characterization of other habitable worlds, it is sure to be exciting.

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The *JWST* Advisory Committee (JSTAC): Maximizing the Scientific Productivity of *JWST*

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The JSTAC's role, distilling its charge down to a key phrase, is to advise the Institute Director on "maximizing *JWST*'s scientific productivity" during its operational life. While this enunciation is simple and focused, the challenges during science operations for a mission of the complexity of *JWST* facing the partner agencies (NASA, ESA, and CSA) and the Institute, and an advisory committee like JSTAC, are similarly wide-ranging and complex. JSTAC members were chosen across the three-agency partnership to have extensive background with space science missions. The Institute's Director formed the JSTAC in 2009 after consulting the partner agencies. The Institute Director appoints the JSTAC, and its 18 members include representatives from the US, European, and Canadian astronomical communities and ex-officio observers from NASA, ESA, and CSA. JSTAC submits recommendations to the Institute's Director. These letters are public: **the JSTAC webpage is here**.

JSTAC meets at the Institute twice per year. Over the years, a broad range of topics has been covered. Meetings typically include presentations from Eric Smith (*JWST* Program Director at NASA Headquarters), Bill Ochs (*JWST* Project Manager at GSFC), and John Mather (*JWST* Senior Project Scientist at GSFC) regarding the status of the *JWST* Project to set the stage for the committee. The focus then shifts to presentations by Institute personnel, organized by Massimo Stiavelli (*JWST* Mission Head), Jason Kalirai (STScI Multi-Mission Project Scientist), and Neill Reid (Science Mission Head). The Director and Deputy Director participate fully in all discussions (as their schedules allow). While presentations provide an essential component, the agenda typically contains extensive discussion time (~50%) so that the committee members can engage with the presenters, with the Institute leadership, and with each other, bringing their experience to bear, so as to assemble recommendations that focus on "maximizing *JWST*'s scientific productivity."

Figure 1: A typical JSTAC meeting seen from the Chair's perspective.

Since 2009, the JSTAC has dealt with numerous topics including: (i) First Look observations (Early Release

Science – ERS); (ii) Large/Treasury/Legacy program proprietary time; (iii) the grant funding levels for General Observers (GOs); (iv) parallel observations; (v) “community fields;” (vi) the length of the Proprietary Time [1] period; (vii) duplications; (viii) proposal submission policies, particularly for Cycle 1; (ix) observing overheads for *JWST*; and others. Every one of these topics involves tradeoffs and subtle challenges to finding an optimal solution for a limited-life mission (required life is 5 years with a goal of 10 years) with a very large science-user community. With a cost to launch of $8B, the JSTAC is also keenly aware of the responsibility that it has, and that we all have in the scientific community, of helping to ensure that the policy-makers and taxpayers of the partner countries get the scientific returns appropriate for such a huge investment of public funding.

In this first article about the JSTAC, I would like to give an overview of the topics that have occupied the committee’s attention over the years. I encourage those interested in more detail to read the letters from the JSTAC to the Institute’s Director on the **STScI JSTAC website**.

First Look/ERS Observations: Some of the earliest discussions with Institute leadership centered on the question of how to ensure that the science community became appraised of the instrumental and scientific capabilities of *JWST*, particularly before Cycle 2 proposals were due. There was joint concern by both JSTAC and the Institute that essentially all early data could be proprietary, and thus not quickly available to community members. The recommended solution was a set of First Look observations (now called the ERS) wherein the programs carried out would exercise the key modes of the *JWST* instruments for a range of science consistent with the four Key science objectives of *JWST*. The data would be made public immediately. Datasets like this have been made available before on *Hubble* and *Spitzer* (e.g., *Spitzer*’s first cycle). The importance of the ERS program for *JWST* is discussed in the JSTAC letter and a ~500 hr ERS is now part of the baseline plan for Cycle 1. **See ERS here**.

Large/Treasury Programs: The JSTAC also recognized the value of programs that provide enhanced datasets to the community. *Spitzer*, *Chandra* and *Hubble* have all utilized such programs with zero proprietary time (called “Legacy” for *Spitzer* and *Chandra*). For *JWST*, the JSTAC has recommended, that the proprietary period continue to be zero for Large, Treasury, and Director's Discretionary time. This was one of the earliest recommendations made by the JSTAC in 2010, and is now part of the baseline plan for *JWST* proposals. **See Large Programs**.

GO Funding: The importance of funding the scientific research from NASA's space science missions has been widely accepted since it was instituted for *Hubble* (and *Spitzer* and *Chandra* and other missions). A key question has been the level of funding needed for *JWST*. In late 2014 the JSTAC instituted a working group to assess the GO funding level so that a recommendation could be formulated. This group evaluated the data and experience from the three Great Observatories (*Hubble*, *Chandra*, and *Spitzer*) and assessed the level of funding needed for GOs for *JWST*. A number of factors indicate that significantly more funding is required than is currently provided for GOs on *Hubble* (e.g., _the on-target time per year relative to_Hubble*is expected to be ~1.6 times greater*). The JSTAC recommendations, along with the report of the working group, were communicated to the Director in its May 22, 2015 letter. **See GO-Funding here**.

Parallel Observations: As *Hubble* has shown, obtaining data in parallel can greatly enhance the overall scientific productivity of a mission. However, *JWST* was not baselined to take parallel science data. This cost-saving measure was understandable in the early days of the mission, but the excellent progress on the mission has opened up the possibility of further consideration of parallel capability. This topic had been discussed for many years by JSTAC. By late 2014, the JSTAC decided that it was time to recommend adding parallel capability, while recognizing that, in the remaining time before launch, not all combinations of modes and instruments could be implemented (**Parallels here**). Some parallel capabilities are expected to be available in Cycle 1.

Community Fields: One of the topics that elicited much discussion in JSTAC during the early years concerned those regions of the sky where large non-proprietary datasets had been assembled from *Hubble*(and particularly from all three Great Observatories—*Hubble*, *Spitzer* and *Chandra*). Given the large investment of Great Observatory time (e.g., ~20 Msec on the HUDF/GOODS-S region) on certain fields with non-proprietary datasets, the JSTAC expressed interest in establishing such regions as open access regions, i.e., no proposal could lock up such fields with proprietary datasets. See the **Community Letter1** from 2010 here. This topic was the subject of continuing (and spirited) discussion within the JSTAC, and also with the SWG and the GTOs (who have 12-

months proprietary time). Eventually the JSTAC decided that just one region stood out enough in the Great Observatories datasets—the HUDF/GOODS-S/CDF-S region—such that it warranted a recommendation that GO data acquired on that region normally have zero proprietary/exclusive access period. See the 2014 **Community Letter2** here.

Proprietary Time: The JSTAC recognized very early in its deliberations that a long 12-month proprietary period greatly impacted the scientific productivity of a limited-life mission. The impact on *JWST* science was enunciated in JSTAC's first letter to the Director in 2010, expanded upon in a later letter in 2010, and then extensively discussed in its March 2014 letter. The JSTAC recognized, as early as in 2010, that "with a 12-month proprietary period, Cycle 4 proposals are the first able to use all Cycle 1 data to do follow-up." In a new, extraordinarily powerful mission like *JWST*, particularly one baselined as a 5 year, 5-cycle mission, follow-up of science discoveries is a key part of "maximizing the science return." If the science community cannot quickly follow up discoveries with new approaches and new observations, the scientific returns from *JWST* will be greatly impacted. See **Proprietary Time here**.

After extensive deliberation and consideration of many different approaches (e.g., <1 data-preserve-html-node="true" data-preserve-html-node="true" data-preserve-html-node="true" data-preserve-html-node="true" year proposal cycles) and other input, as detailed in the 2014 letter, the JSTAC recognized that the only approach that would make a significant difference was a 6-month proprietary period. There are many aspects that played a role in JSTAC's thinking, but one that was very surprising to JSTAC, concerns the long time (>2 years) to publication of science data (see Figure 2). This has interesting implications for discussions of the proprietary period. Now that *Hubble* is moving to 6-months proprietary time, it is anomalous that *JWST* continues with 12 months. A comprehensive summary from early 2016 regarding proprietary time, giving updates since the 2014 JSTAC letter is in the **JSTAC presentation here**.

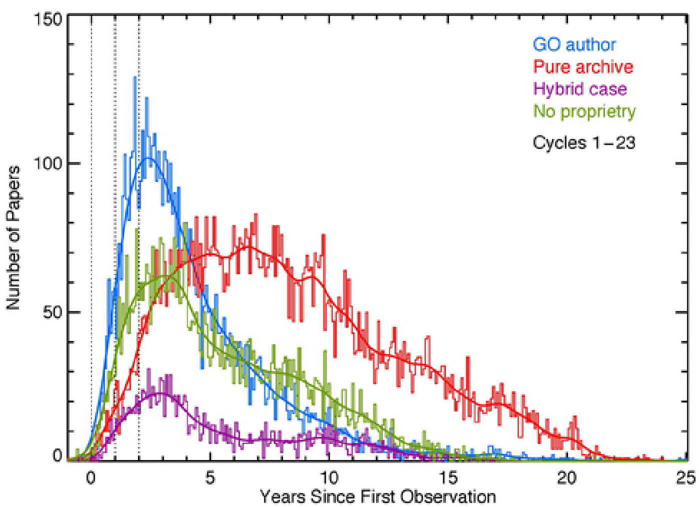

Figure 2: There is a substantial delay (on average >2 years) in the time between the acquisition of *Hubble* data and its publication. This is true regardless of data type or proprietary period. It is clear that many of the concerns about shorter proprietary periods are not borne out by the data on publication timescales. These *Hubble* data were assembled by Jeff Valenti and Karen Levay. The >2-year timescale to publication is similar on *Spitzer* and *Chandra*.

Future Topics: The JSTAC's recommendations regarding Cycle 1 proposals will be the subject of a future article, as will a more extensive discussion of proprietary time. This latter topic has occupied the JSTAC extensively over the years and deserves a more thorough exposition. JSTAC has also set up a Data Processing Working Group (JDPWG) to explore data processing questions and issues in more depth. See the 2016 letter re the **Data Processing Working Group**.

Two key factors have contributed greatly to the value of the JSTAC's recommendations: (1) the experience and commitment of JSTAC's members, and (2) the thoughtful and thorough effort by Institute staff to provide the needed background and analysis for the committee to be well informed on issues. *JSTAC would not have been able to do what it has done without the excellent, productive, and very open dialog with the Institute's leadership and staff*.

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[1] Note that NASA also calls "Proprietary Time an "Exclusive Use Period."

State of the *Hubble* Observatory

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Now in its 26th year of operations, *Hubble* is still going strong, producing science that continues to challenge and expand our understanding of the universe. From predicting supernovae, to finding the most distant spectroscopically confirmed galaxy, to detecting water-vapor plumes above the surface of Europa, the breadth of *Hubble*'s science is vast and continues to grow. After 26 years and over 142,000 orbits of the Earth, *Hubble* is a healthy, mature observatory, and all subsystems are operating in a nominal status; extrapolations predict mission continuation beyond 2020. In this *Newsletter* article, we provide a brief "State of the Observatory" overview of recent activities.

At this time, *Hubble* operations are running smoothly. There has been a remarkable absence of safemode entries and instrument hang-ups. The planning and scheduling team has been especially successful in crafting efficient long-range plans, with an average of 86.5 orbits per week in the first 30 weeks of Cycle 23, compared with an average of 84.0 orbits per week in Cycles 17–22.

Hubble 2020

In Spring 2015, a call for white papers was issued to solicit community input on initiatives that will enhance significantly *Hubble*'s scientific legacy over the next five years of observations. The *Hubble* 2020 vision was described in the 2015 vol. 32, issue 01 *Newsletter* article by Ken Sembach, "**Towards a 2020 Vision for the *Hubble Space Telescope***."

Three main recommendations are being implemented as a result of this community input. The first is a continuation of the enormously successful UV initiative, started in Cycle 21, and the second is the initiation of a *James Webb Space Telescope* Preparatory Initiative, starting with the current Cycle 24. Read more about these in the following subsections. The third outcome of the white papers was a recommendation that the Institute should provide an opportunity for the community to submit very large proposals—similar to the enormously successful Multi-Cycle Treasury Program of Cycles 18–20—with a particular emphasis on science topics that are unique to *Hubble*, including UV science. Starting in Cycle 24, these very large programs (more than 350 orbits) will be incorporated in the regular proposal review, with explicit instructions to the TAC, and may be subsidized from Director's Discretionary time. The orbit allocation will be shared between Cycles 24 and 25. Early indications after the Cycle 24 proposal deadline are that the community has responded with overwhelming enthusiasm to this opportunity to propose for larger projects.

Hubble, by any definition a truly Great Observatory, remains at the forefront of observational astrophysics more than 25 years after its launch in 1990, thanks to the optical quality of the telescope, the excellent pointing performance of the spacecraft, the suite of instruments, the quality of the data and archive, and the experienced operations teams. The mission technical objectives reflect the goal to maximize science in *Hubble*'s remaining years. This goal, for a five-year horizon, should not jeopardize longer-term operations and future scientific productivity, especially since *Hubble* continues to operate near peak performance nearly seven years after Servicing Mission 4.

In the fall of 2015, the GSFC Flight Dynamics Facility analysis indicated reentry of the spacecraft no earlier than 2028, and most likely in 2036. With the exception of the gyroscopes, and the expected depletion rate of the COS FUV detector simply due to use, the spacecraft subsystems and instrument health and performance status have not significantly changed in the last several years. The methodology employed in the 2013 NASA Engineering and Safety Center (NESC) report, and recently updated for the NASA Senior Review of operating missions (see below), established the same familiar high confidence that *Hubble*'s instruments and subsystems will remain operable through the next five-year period. The NESC analysis shows that there is a >98% probability of having WFC3 and COS available in 2020. The *Hubble* team continues to pay close attention to the effects of use and on-orbit aging as we strive to optimize the long-term use and performance of the observatory.

UV Initiative

The UV Initiative, in place since Cycle 21, recognizes the unique capability that *Hubble* has in accessing the ultraviolet (UV) portion of the electromagnetic spectrum (wavelengths less than 3200 Angstroms), and encourages proposals that seek to utilize these resources. Nearly all categories of proposals (Small, Medium, Large, and Treasury GO proposals, as well as Regular Archival, Legacy Archival, and Theory proposals) are eligible for the UV Initiative. Telescope Allocation Committees (TACs) have been encouraged to devote at least 40% of their orbit allocation to UV-specific science; these levels are advisory, not quotas, and all accepted *Hubble* proposals must independently meet the high bar of outstanding scientific quality. In Cycles 21 through 23, a total of 305 accepted observing programs have made use of the UV Initiative. The science programs being conducted under the UV Initiative span almost all science categories (see Figure 1). The UV Initiative continues in Cycle 24 and beyond. Bibliographical information for accepted UV Initiative programs can be found at **this link**.

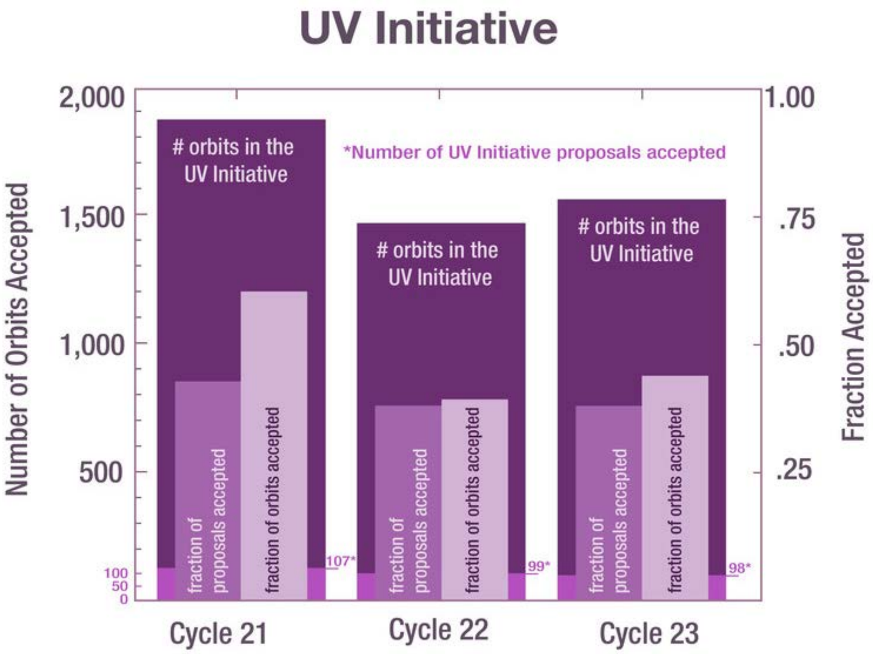

Figure 1: Graphs summarizing UV initiative.

The LEGUS (Legacy ExtraGalactic UV Survey; a GO Cycle 21 Large Program) is a conspicuous example of the breakthrough science enabled by the UV initiative (Figure 2). LEGUS (**http://legus.stsci.edu**) is focused on providing a critical missing piece in the star-formation puzzle: connecting star formation at the parsec-sized scale of individual stars, stellar clusters, and associations to kiloparsec-scale patterns of star formation in galaxy disks. Observations with LEGUS—five-band imaging in *NUV*, *U*, *B*, *V* and *I* filters, for 50 nearby galaxies with WFC3 and ACS imaging in the *Hubble* archive—enable reconstruction of the recent star-formation histories (SFH) at accuracies of about 10 Myr, and break the age-extinction degeneracies on small scales.

Figure 2: Observations of the nearby spiral galaxy NGC 6503 in optical and UV light trace the spatial and temporal evolution of star formation within galaxies, from the pc-sized scales of stars to the kpc-sized scales of star formation.

Hubble's spatial resolution and wide-band coverage display clustering of star formation in these galaxies, revealing hierarchical structuring of star formation (Elmegreen et al. 2014; Gouliermos et al. 2015). The self-similarity of structures of star formation down to parsec scales is consistent with turbulence playing an important role in triggering star formation (Elmegreen et al. 2014). In addition, LEGUS observations determine the recent star-formation histories of stars and clusters and their impact on the UV star-formation rate calibrations. Calzetti et al. (2015) determined from extraordinarily well-sampled spectral energy distributions of young massive clusters that star formation in one nearby dwarf starburst galaxy has become more concentrated over the last 15 Myr. The wide range of galactic environments and broad wavelength coverage enable a host of additional science; LEGUS observations have already been exploited for studies of supernova progenitors and their environments (Van Dyk et al. 2015) and investigations of the role and fate of star clusters in relation to the natal environment (Grasha et al. 2015).

Preparing for the *James Webb Space Telescope*

The anticipated launch of the *James Webb Space Telescope* in October 2018 will bring extensive photometric and spectroscopic capabilities spanning the 0.7–28 micron wavelength range. Some science programs to be undertaken by *Webb* may require or be enhanced by *Hubble* observations. The *JWST* Initiative, starting in Cycle 24 and recommended as a result of the *Hubble* 2020 initiative, provides an opportunity to obtain observations with *Hubble* that complement and enhance the scientific impact of *Webb* observations. *Hubble* has capabilities at UV and optical wavelengths that complement and extend *Webb*'s capabilities, and there are some science goals which may be achieved only with the combination of both *Hubble* and *Webb* observations. All GO programs are eligible for the *JWST* Initiative, but other proposal categories (SNAP, AR, Theory) are not. Proposals must be tackling science questions that can only addressed with a combination of *Hubble* and *Webb* observations. Proposals will be addressed on the science case of the joint program, even if there is a limited science return from the proposed *Hubble* data.

The nominal science planning timeline for *Webb* (described in Jason Kalirai's **article** in the 2015, vol. 32, issue 02 Newsletter) has a *JWST* GO Cycle 1 proposal deadline in February 2018, with proposal selection taking place in May 2018. Astute *Hubble* observers will note the overlap with the traditional cycle for *Hubble*, which has a proposal deadline in early April, and Telescope Allocation Committee (TAC) meeting in early June. The Institute will host the TACs for both observatories; such a close conjunction would likely cause significant logistical hurdles, in addition to inducing community weariness about proposal submission and evaluation. Options are currently under consideration for alterations to the proposal submission and review schedules to forestall any issues with jointly operating two great observatories.

Cycle 23 Mid-Cycle Proposal Selection

The Cycle 23 Call for Proposals contained an additional new category of GO proposals that allows for a faster response to new discoveries than the annual proposal cycle allows. This expands upon the Director's Discretionary Proposal category, which is generally limited to observations of time-critical events. Mid-cycle proposals provide the community with an opportunity to capitalize quickly on recent discoveries through short (≤5 orbit) proposals for observations of newly discovered astrophysically interesting objects. The proposed observing program needed to have minimal constraints in order to maximize scheduling flexibility and ensure ability to execute observations in the current cycle. Up to 200 orbits was available at each of two mid-cycle proposal deadlines.

The two solicitations had rolling submissions, with cutoffs of October 1, 2015 and January 31, 2016. Members of the community who have contributed to recent *Hubble* TAC reviews did the scientific review. A total of 13 programs involving 52 orbits was approved after the inaugural mid-cycle proposal selection cutoff in October, and a further 9 programs involving 34 orbits were approved after the second call. Proposals submitted after the January

31 cutoff were held over for consideration, along with proposals submitted for the Cycle 24 Call for Proposals. A listing of the approved programs from the mid-cycle call can be found in Table 1. This mid-cycle proposal selection is expected to continue in Cycle 24.

Table 1: Listing of Accepted Mid-cycle Proposals

Accepted Cycle 23 Mid-Cycle Proposals

Name	Institution	ESA Member	Title
Zachory Berta-Thompson	MIT		Hydrogen Escape from an Earth-size Exoplanet: a Reconnaissance Study
Rychard Bouwens	Universiteit Leiden	yes	Preparing for JWST through Constraints on the Bright End of the z ~ 9 LF from CANDELS
David Enrenreich	Observatoire de Geneve	yes	Atmospheric Escape from the Closest Super-Earth
Thomas Evans	University of Exeter	yes	Characterizing an Exteme Planet of the Verge of Tidal Disruption
Boris Gaensicke	The University of Warwick	yes	AR Sco: The First White Dwarf Pulsar?
Frederick Hamann	Univeristy of Florida		A Remarkable New Transient Outflow in the Quasar PG 1411+442
David Jewitt	UCLA		Hubble Investigation of Active Asteroid 324P/La Sagra
Mercedes Lopez-Morales	Smithsonian Institution Astrophysical Observatory		Atmospheric Sodium and a Precise Radius for the Closest Super-Earth
Carlo Manara	ESA-ESTEC	yes	The HST-ALMA connection: Measuring the FUV Spectrum of a Newly Discovered Transition Disk down to the H_2 and CO Photodissociation Regime
Bruce	Catholic		Identifying the Progentior of a

McCollum	University of America		New Red Transient
Ivana Orlitova	Astronomical Institute, Academy of Sciences of CR		Lyman Alpha Halo in a Confirmed Lyman Continuum Leaker
Jonathan Tan	University of Florida		Peering to the Heart of Massive Star Birth
Siyi Xu	European Southern Observatory -- Germany	yes	A White Dwarf with an Actively Disintegrating Asteroid
Vincent Bourrier	Observatoire de Geneve	yes	UV Exploration of two Earth-sized Planets with Temperate Atmospheres
J. Howk	University of Notre Dame		Pop III Material Found 6 Gyr after the Big Bang? COS Constraints on the Lowest-metallicity Gas at z < 1
David Jewitt	UCLA		Comet P/2010 V1 as a Natural Disintegration Laboratory
Andrew Newman	Carnegie Institution of Washington		Resolving the Stellar Populations, Structure, and Kinematics of the NIR-Brightest Lensed Galaxy at z = 2
Keith Noll	NASA Goddard Space Flight Center		Trojan Binary Candidate: A Slow-Rotating Mission Target
Renske Smit	Durham University	yes	Identifying z > 12 galaxies with JWST: What Sources Produce Strong UV Emission Lines?
David Sobral	Lancaster University	yes	The Gas-metallicity and the ISM of the Brightest Lyman-alpha Emitter at z = 6.6: Metal-free?
Jonathan Tan	University of Florida		Peering to the Heart of Massive Star Birth. II. Completion of the Eight-Source Pilot Survey
Michael Wong	University of California-Berkeley		A New Dark Vortex

Hubble at the AAS

A special session at the AAS Winter meeting in Kissimmee, FL entitled “Hubble Space Telescope: A Vision to 2020 and Beyond,” showcased recent developments aimed at giving new life to the instruments and science with *Hubble*. Topics addressed plans for the next several years of operations; to extend *Hubble*’s lifetime into the *Webb* era and remain a forefront observatory while doing so, by maximizing the scientific output with new observing modes, as well as accelerating the pace of discovery with catalogs and archive tools. The session was recorded, and may be viewed at the following site: **https://webcast.stsci.edu/webcast/detail.xhtml?talkid=5037&parent=1**.

Talk titles and speakers in the special session were:

“Maximizing the Scientific Return and Legacy of the *Hubble Space Telescope* Mission,” Jennifer J. Wiseman (NASA/Goddard Space Flight Center)

“*Hubble Space Telescope*: A Vision to 2020 and Beyond: The Hubble Source Catalog,” Louis-Gregory Strolger (STScI)

“High precision astrometry with *HST*/WFC3 Scanning mode: Parallaxes of two Galactic Cepheids,” Stefano Casertano (STScI); Adam G. Riess (JHU, STScI)

“The new European *Hubble* archive,” Guido De Marchi; Maria Arevalo; Bruno Merin (ESA)

“Near-infrared Grism Spectroscopy with the Wide Field Camera 3: Insights from the 3D-*HST* Survey,” Ivelina G. Momcheva (Yale University, STScI)

“The Ultraviolet Spectroscopic Legacy of *HST*,” Thomas R. Ayres (U. of Colorado)

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Search

The Legacy ExtraGalactic UV Survey (LEGUS)

Daniela Calzetti, *calzetti@astro.umass.edu*, and the LEGUS Team,
https://archive.stsci.edu/prepds/legus/team.html

Search

The combination of UV capability, high-angular resolution, and large field of view afforded by the *Hubble Space Telescope* is the foundation of the Legacy ExtraGalactic UV Survey (LEGUS), GO-13364. LEGUS, a Cycle 21 *Hubble* Treasury program, was designed with the main goal of providing a definite characterization of the links between star formations on two fundamental scales: those of individual stars, stellar clusters, and associations on parsec scales; and of galaxy disks on kiloparsec scales (Calzetti et al. 2015b).

In order to achieve its science goal, LEGUS has obtained multi-color images of 50 nearby star-forming galaxies, in the distance range ~3–16 Mpc. Wavelength coverage spans five bands (*NUV*, *U*, *B*, *V*, and *I*) by combining new WFC3 observations with archival ACS imaging data, when available. The galaxies were carefully selected to sample the full range of galaxy mass, morphology, star-formation rate (SFR), sSFR (specific SFR = SFR/mass), metallicity, internal structure (rings, bars), and interaction state found in the Local Volume where *Hubble* can resolve and age-date young stellar populations on parsec scales.

Many of the galaxies are well-known, iconic ones, with a wealth of additional information available in the MAST archive. The multi-color images (Figure 1) are used to secure complete inventories of the young stars, star clusters, and structures of the galaxies, together with the characterization of their ages, masses, and extinctions. For this, the ultraviolet band provides critical leverage, as it enables breaking the degeneracy between age and extinction. The goal of a complementary Cycle 22 *Hubble* program (GO-13773) is to obtain narrow-band imaging in the light of the Hα emission line for many of the LEGUS galaxies in order to trace the regions of recent massive star formation.

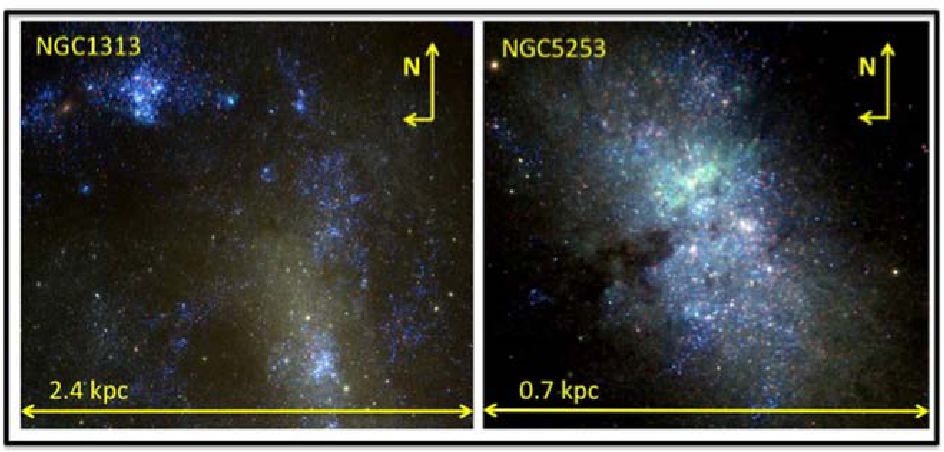

Figure 1: Details of the central regions of two LEGUS galaxies, NGC 1313 (4.39 Mpc distance, left) and NGC 5253 (3.15 Mpc distance, right). The images are color-composites using the *NUV*+*U* (blue), *B*+*V* (green), and *I* (red) bands. For NGC 1313, the image shows one of the spiral arms departing from the nucleus (located at the bottom-right of the image), while for the dwarf NGC 5253, the entire star-forming central region is shown. The diffuse green light close to the center of NGC 5253 is [O III] forbidden line emission emerging in the *V* band. The images highlight the complexity of the stellar structures in these galaxies, especially those containing young (blue) stars.

Among the specific science objectives of the project, we list: quantification of the evolution both in space and time of the clustering of star formation; discrimination among models of star cluster formation and evolution; determination of the recent formation histories of stars and clusters and their impact on the UV-star-formation-rate calibrations. We provide here a brief summary of some of the initial results.

Most stars are formed in clustered structures forming a continuous, scale-free hierarchy from parsecs to kiloparsecs (Lada & Lada 2003; Elmegreen 2003; Bressert et al. 2010). These structures are expected to arise from the self-similar distribution of a turbulence-dominated interstellar medium (Elmegreen & Efremov 1997), mediated by magnetic fields and outflow feedback (e.g., Krumholz et al. 2014). The densest peaks of the hierarchy likely survive disruption by a host of both internal and external mechanisms, and evolve as gravitationally bound star clusters.

Building upon earlier results, the LEGUS collaboration has been characterizing the properties of these structures using both stars and star clusters as tracers, and a number of techniques, including image smoothing and two-point correlation functions. The latter measures the degree of clustering of the observed data relative to a random distribution. Using ultraviolet images, which trace young star-forming structures, Elmegreen et al. (2014) found that while hierarchically distributed structures from several up to a few hundred parsecs are common in galaxies, starburst galaxies show a higher fraction of projected areas filled with star formation relative to more quiescent galaxies. The distribution of young stars is in self-similar, fractal structures from ~20 pc to ~2.5 kpc in the ring galaxy NGC 6503, but they diffuse across the galaxy within ~60 Myr (Gouliermis et al. 2015). The star-cluster distribution is also within self-similar structures, with a correlation length of about 300 pc (Figure 2; Grasha et al. 2015, 2016).

When star clusters are divided according to their morphological characteristics, the compact clusters are significantly less clustered than the ‘multi-peak’ clusters (Figure 2). The three morphological categories of cluster candidates used by the LEGUS collaboration are likely to reflect physical differences as well: the compact (class 1) sources may be relaxed, massive clusters, the ‘elongated’ (class 2) sources are unrelaxed clusters, while the ‘multi-peak’ (class 3) sources are likely stellar associations. The associations, furthermore, disperse over a ~50 Myr timescale (Adamo et al. 2016), in agreement with the clustering analysis which suggests that clusters randomize within ~40–50 Myr (Grasha et al. 2016).

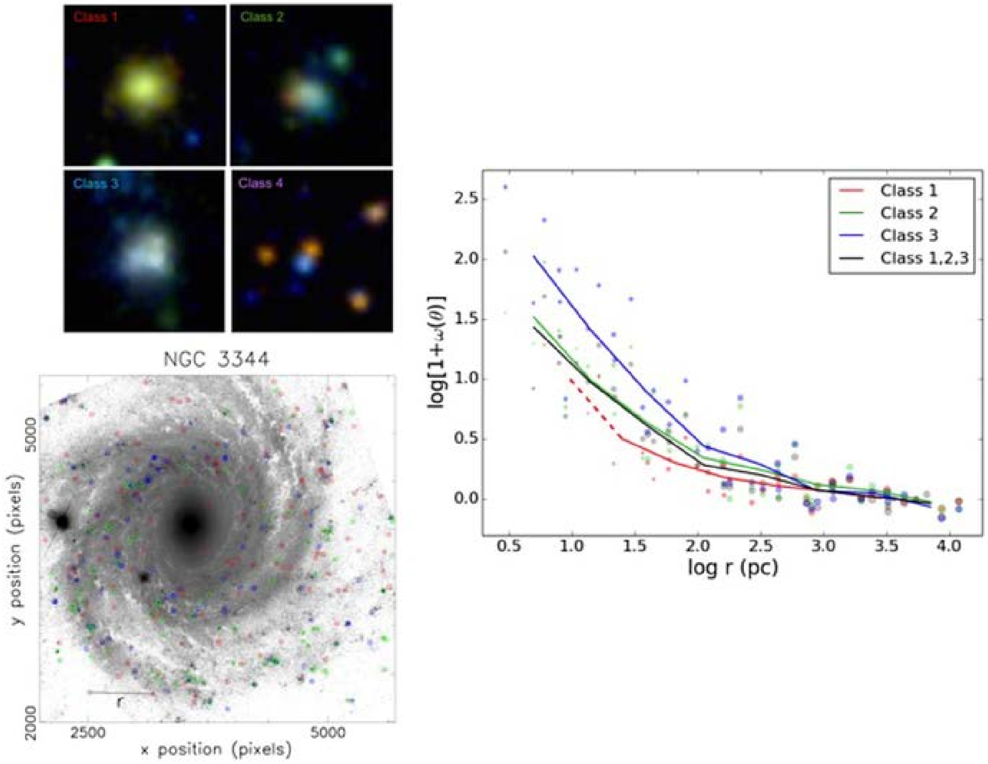

Figure 2: (*top left*) The cluster classification scheme adopted by the LEGUS collaboration, shown on three-color composite (*U*,*V*,*I*) image cut-outs (Adamo et al. 2016): Class 1—symmetric, compact cluster; Class 2—concentrated object with some degree of asymmetry; Class 3—multiple-peak system; Class 4—spurious detection (background galaxies, bright stars with extended halos, asterisms, artifacts). (*bottom left*) Class 1, 2, 3 (red, green, blue) cluster candidates are shown as circles, on a grayscale image of the LEGUS galaxy NGC 3344. The segment marked 'r' at the bottom-left of the image connects two clusters of the same class; pairs of clusters all sharing the same separation 'r' (in pc) are counted within each galaxy to construct the two-point correlation function. (*top right*) The two-point correlation function, obtained by combining cluster pairs from six different LEGUS galaxies, is shown for Class 1, 2, and 3 clusters separately, together with the cumulative function. More strongly clustered distributions display a sharper rise towards small separations. A random distribution would show as a horizontal line at $\log[1+\omega(\theta)] = 0$ (Grasha et al. 2016).

Because of the wide range of galactic environments and the broad wavelength coverage it probes, LEGUS enables a host of additional science, including, but not limited to:

- studies of supernova progenitors and their environments (Van Dyk et al. 2015);
- investigations of the role and fate of star clusters in relation to the natal environment (Calzetti et al. 2015a);
- analyses of cluster spatial distribution as discriminators for models of spiral galaxies (Dobbs et al. 2016);
- tests of stellar-population models accounting for a range of astrophysical inputs, and analysis of impact on observed cluster properties (Krumholz et al. 2015; Wofford et al. 2016); and
- studies of the physics of massive stars (Smith et al. 2016).

The first high-level data product delivery of LEGUS imaging data was performed in September 2015, and the multi-wavelength, aligned images are available at: **https://archive.stsci.edu/prepds/legus/dataproducts-public.html**.

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New Science from Old Data: Finding Debris Disks in the *Hubble* Archive

Search

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Major breakthroughs in our knowledge of exoplanet populations have occurred over the last 10 years. With more than 2300 exoplanets detected by the *Kepler* mission, we now know that our solar system is not unique and that planets are ubiquitous in our galaxy. Two out of three sun-like stars have a planet the size of Neptune (or smaller) within 0.75 AU (Dong & Zhu 2013), while every dwarf M star—much more numerous than stars like our Sun—hosts at least two planets within similar orbits (Dressing & Charbonneau 2015). Yet several major questions about extra-solar planets remain open such as characterizing their structures and compositions as well as investigating if some harbor life. Clearly we must also learn more about their formation mechanisms. Understanding formation processes requires completing our planet census by detecting and characterizing massive exoplanets on wider orbits. As well, imaging the debris and dust left over from their formation can let us study their birthplaces and analyze their core compositions.

Large-orbit exoplanets are very difficult to find. They have orbital periods too long to be efficiently and unambiguously detected by indirect methods, such as transit or radial velocity measurements. They are also typically too dim to detect with direct imaging, that is, sufficiently distant from the parent star and bright enough to be identified. Such detections thus far have been limited to only very massive and young systems still warm enough to be self-luminous in infrared wavelengths.

Astronomers have learned the hard way that that new methods are necessary to push sensitivity limits, and improve the detectability of these systems. Dedicated instruments equipped with starlight-suppression systems, and exquisite wavefront controls, are capable of dimming the star by a factor of 1 million. Also, we require optimizing observing strategies to monitor the variability of the star due to instrumental instabilities, and developing post-processing algorithms to subtract the residual starlight from the images and finally reveal faint exoplanets. Through these techniques, and with instruments such as the Gemini Planet Imager (GPI), we are now able to detect giant planets a few times more massive than Jupiter on ~10 AU orbits around young, 20 Myr-old stars such as 51 Eridani b (Macintosh et al. 2015; see Figure 1). We can also study the atmospheric structure and composition of such objects using new methods.

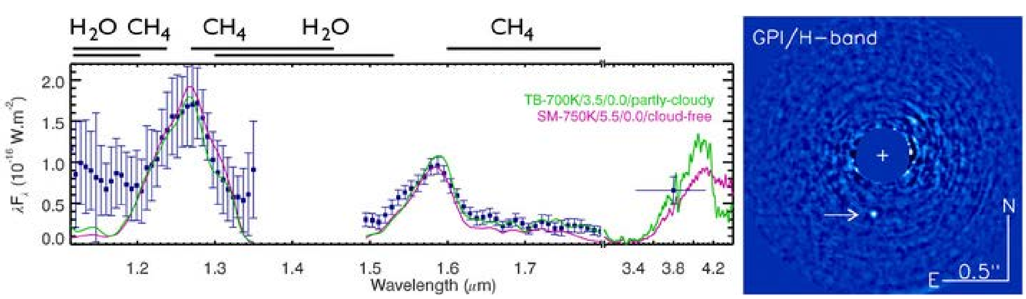

Figure 1: Image and spectrum of 51 Eri b discovered by the GPI instrument (from Macintosh et al. 2015). The planet spectrum shows evidences for methane and water content. The planet's low brightness and young age is such that it can be explained by two different formation models.

The *Hubble Space Telescope* was designed well before the advent of these new technologies, and its "first-generation" coronagraphs were not optimized for finding such faint circumstellar objects. Recently developed post-processing algorithms might be applied to *Hubble*'s archival data to improve starlight subtraction methods to reveal faint circumstellar objects. This was the goal of the recently completed Archival Legacy Investigations of Circumstellar Environments (ALICE) project, led by R. Soummer. As part of this program, we consistently re-analyzed the entire archive of the NICMOS near-infrared data, spanning a decade from 1997 to 2008, achieving new starlight subtractions 100 times more precise than previously achieved.

NICMOS had been used to search for exoplanets around stars in the solar neighborhood. While no exoplanets were imaged, five debris disks were successfully detected with NICMOS, revealing dust left over from planet formation on large orbits around these stars, and similar to our solar system's Kuiper belt.

Using advanced post-processing algorithms and building on the wealth and diversity of the NICMOS archive to monitor the instrument's slightest instabilities enabled us to subtract the residual starlight 100 times more precisely from NICMOS images than was previously achieved. Three exoplanets around the 50 Myr-old HR 8799, previously discovered with ground-based telescopes, were newly uncovered in the NICMOS data with this method. By looking further back into the 10 year-old NICMOS dataset and measuring the motion of the planets, these detections enabled the measurement of the planets' orbital parameters with unprecedented precision (Soummer et al. 2011).

Using the ALICE program, several additional planet-candidates were detected around other nearby stars, and the team is now working to confirm these detections. The program also has found 15 debris disks that were previously undetected in the NICMOS archives—11 of them never seen before by any instruments in this wavelength regime (Figure 2). Thanks to additional observations in complementary wavelengths, we will be able to study their structure and composition, as well as studying how they may be affected by undetected planets on nearby orbits by analyzing their morphology (shape, asymmetries, dust extent). Moreover, these new detections brought the number of debris disks imaged in near-infrared wavelengths to 31, which now enables interesting comparative studies of their physical properties and composition with respect to the characteristics of their host stars (age and mass).

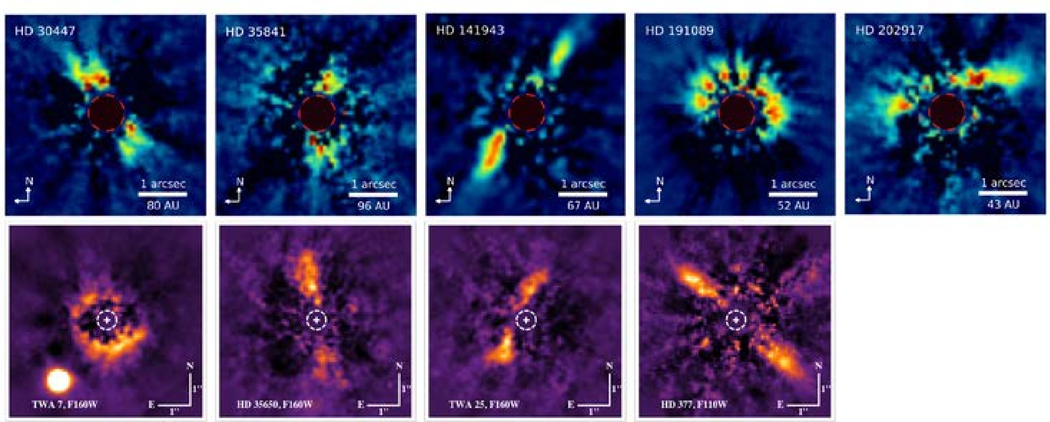

Figure 2: Nine out of the 15 debris disks detected by the ALICE project by re-analyzing old archival *Hubble*-NICMOS data with advanced post-processing algorithms (from Soummer et al. 2014 and Choquet et al. 2016). These disks are formed by cold dust grains leftover from planet formation on large orbits around the stars, like our Kuiper belt.

Acknowledgements: This project was supported by NASA through grants HST-AR-12652.01 (PI: R. Soummer) and HST-GO-11136.09-A (PI: D. Golimowski), and by STScI Director's Discretionary Research funds, and was made possible by the Mikulski Archive for Space Telescopes (MAST) at STScI, which is operated by AURA under NASA contract NAS5-26555.

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Search

Hubble Extends Our Cosmic Horizon Back Through 97% of Cosmic History

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In *The Realm of Nebulae*, Edwin Hubble wrote: “The history of astronomy is a history of receding horizons,” a quote which could not be more fitting to describe the story and the discoveries of the *Hubble Space Telescope*. During its 26 years in space, *Hubble* has steadily pushed our observational horizon to earlier and earlier cosmic times and transformed our view and understanding of how galaxies built up and evolved in the early universe. Starting from the *Hubble* Deep Field (Williams et al. 1996) and the discovery of $z \sim 4$ galaxies from about 12 billion years in the past (Madau et al. 1996), *Hubble* has now found galaxies as far back as $z \sim 10$, when the universe was only about 3% of its current age (e.g., Bouwens et al. 2011; Ellis et al. 2013; Oesch et al. 2014). This is a stunning achievement, and one that few expected to be possible at the time of *Hubble*’s launch.

The latest of *Hubble*’s accomplishments to expand our cosmic horizon of galaxies came as a surprise even for astronomers today. Using the powerful WFC3 infrared camera which was installed in 2009, *Hubble* discovered—and then spectroscopically confirmed (Oesch et al. 2016)—a very luminous galaxy at $z = 11.1$, only 400 million years after the Big Bang. This galaxy, named GN-z11, is the farthest object ever seen in the universe. It takes astronomers into a realm once thought only to be reachable with NASA’s upcoming *James Webb Space Telescope*. The new *Hubble* observations push back the frontier of galaxies that have accurately measured distances by a large margin: the previous record-holder was found at $z = 8.68$, more than 150 Myr after GN-z11 (Zitrin et al. 2015).

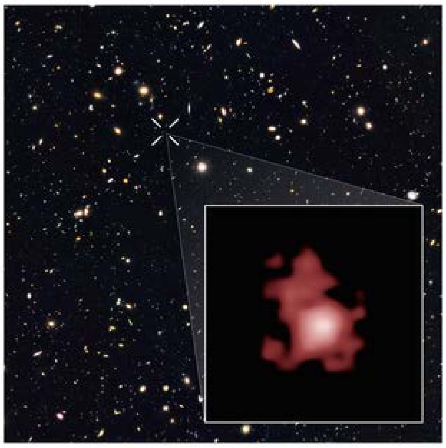

Figure 1: A zoom into the GOODS-North field, where the galaxy GN-z11 (shown in the inset) was detected based on images from the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011). Using slitless spectroscopic observations with *Hubble*, the redshift of GN-z11 was measured to be $z = 11.1$, making this the most distant object ever discovered. The image shows the galaxy as it was 13.4 billion years in the past, just 400 million years after the Big Bang, when the universe was only 3% of its current age. Credit: NASA, ESA, P. Oesch (Yale University), G. Brammer (STScI), P. van Dokkum (Yale University), and G. Illingworth (University of California, Santa Cruz).

There is a fascinating story here. It turns out that the galaxy GN-z11 was seen in observations with WFC3’s IR predecessor, NICMOS, back in 2008. It was then thought to be too bright to really lie at such an extreme distance (Bouwens et al. 2010). When combined with the uncertain redshift from the noisy data, this NICMOS detection was not taken very seriously at that time. Astronomers continued to expect that the galaxy population at $z \sim 10$–12 would be very faint, requiring very deep observations to be detectable. Surprisingly, however, most of the $z > 9$ galaxies currently known were not discovered in ultra-deep imaging such as the *Hubble* Ultra-Deep Field, but in shallower surveys covering wider areas. GN-z11 was identified among a sample of four luminous $z > 9$ galaxy candidates in observations with the WFC3/IR camera in the GOODS-North field as part of the public CANDELS survey (Oesch et al. 2014).

The new images with WFC3/IR convinced astronomers that GN-z11 was highly likely to be at very early cosmic times. Nonetheless, proof in the form of a spectroscopic redshift measurement was required. This was the goal of *Hubble* program GO-13871 (PI: Oesch). While previous distance measurements for early galaxies mostly relied on the identification of the redshifted Lyα emission line with ground-based 10m-class telescopes, it has recently been found that these Lyα emission lines disappear rapidly for galaxies beyond $z > 6$ (e.g., Schenker et al. 2012; Treu et al. 2013). This can be explained by the increasingly neutral intergalactic medium at these early cosmic times, which scatters and absorbs the Lyα photons.

However, *Hubble* does not require a Lyα emission line for a redshift measurement. Orbiting outside of Earth's atmosphere, a key advantage of *Hubble* is that it is subject to much lower background radiation in the near infrared compared to ground-based telescopes. The use of grism spectroscopy with the very sensitive WFC3/IR camera allowed astronomers to successfully detect the continuum of GN-z11 (at 26th magnitude). In particular, a clear break was measured at 1.47 micron, which indicates a redshift of $z = 11.1$, even higher than the original estimate based purely on the photometry. This redshift is very close to the limit of what *Hubble* will ever be able to see, as galaxies even further away will shift out of the wavelength range covered by *Hubble*'s instruments.

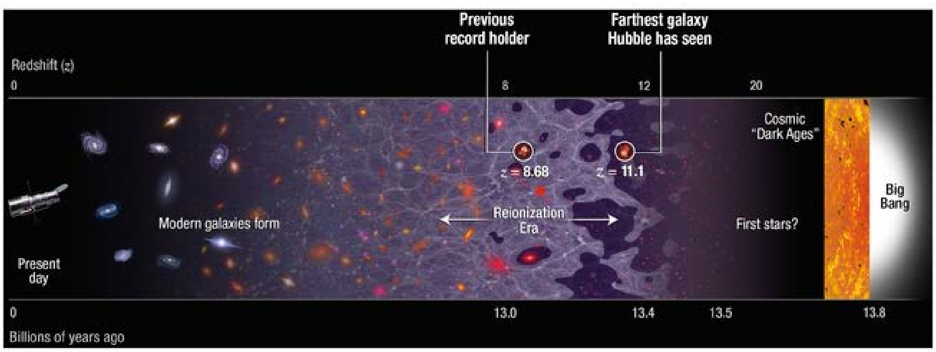

Figure 2: The measurement of GN-z11 pushes our cosmic horizon close to the formation of the first galaxies. This discovery provides a very tantalizing preview of many even more distant galaxies **Webb** will be able to detect and characterize by the end of this decade. The graphic shows a timeline of the universe, stretching from the present day (left) to the Big Bang (right). Credit: NASA, ESA, B. Robertson (University of California, Santa Cruz), and A. Feild (STScI).

The discovery of GN-z11 at $z = 11.1$ in the current *Hubble* images challenges our theoretical understanding of galaxy formation in the early universe. The latest models have all predicted that existing *Hubble* surveys would be too small to detect such a luminous galaxy, and such a detection would require a search area 10–100 times larger (e.g., Mashian et al. 2015; Trac et al. 2015; Mason et al. 2015; Waters et al. 2016). GN-z11 may thus indicate something fundamentally new about how efficiently early galaxies formed out of the primordial gas after the Big Bang. Larger area surveys are now needed to more accurately measure the cosmic abundance of galaxies as bright as GN-z11 in the early universe. This can already be achieved with a substantial investment of *Hubble* time, and would be a striking legacy for *Hubble*. It will certainly be done with NASA's planned *Wide-Field Infrared Survey Telescope* (*WFIRST*), which will have the ability to find thousands of similarly bright and distant galaxies.

These findings also have exciting consequences for what astronomers will be able to discover with *Webb* after its launch in 2018. The confirmation of GN-z11 proves that galaxy build-up was well underway at 400 Myr after the Big Bang. GN-z11 was detected in images taken with the *Spitzer Space Telescope*, which indicates that it had already built about a billion solar masses in stars. This build-up must have started very soon after the Big Bang.

With *Hubble*'s discovery and spectroscopic confirmation of GN-z11, we have now explored 97% of cosmic history. While *Hubble* is reaching its limits in further extending our cosmic horizon, *Webb* will soon take over and take us back to a time when galaxies were first forming. The progenitors of GN-z11 will be easy targets for *Webb* well beyond $z = 11$ and, true to the statement of Edwin Hubble, the history of astronomy will continue to be rewritten.

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Our Place in Space: *Hubble* Images and Inspired Art

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Enhancing the connection between science and art

For more than two decades, *Hubble*'s images have engaged the public and bolstered interest in science and astronomy. Scientists and the public alike have been inspired by the fundamental questions that are often triggered by *Hubble* discoveries: Where do we come from? Where we are going? Are we alone? The new exhibit, *Our Place in Space*, is designed to capture the spirit of wonder and inspiration generated when we pause to ponder humanity's place in the grand scheme of the cosmos. To do this in a public exhibit, we ask astronomers and artists to communicate their interpretation of where we are and belong, how our past affects us, and what our future might be —through imagery and art. The exhibit's themes present humanity's adventure in space from local exploration in the solar system out to discoveries at the edge of the universe.

Our Place in Space, sponsored by ESA and in cooperation with NASA, is a portable, adaptable exhibit, based on an idea by Antonella Nota and Venetian art curator Anna Caterina Bellati. It showcases stunning *Hubble* imagery documenting our presence in the universe, while the art reflects the impact that *Hubble* has made on culture and society.

Figure 1: Opening venue for the *Our Place in Space Exhibit* (February/March 2017): The Palazzo Cavalli Franchetti in Venice.

Exhibit components

The exhibit, constructed to be portable and adaptable to the specific venue and the locale, is adaptable to venues large and modest. The key themes of the exhibit are "What is our place in the solar system, galaxy, local universe, and cosmos?" Each theme is articulated through relevant *Hubble* images accompanied by artistic interpretations of the same question. Through a local, associated art curator, connections will be made to the local art community to create "local" interpretations of the themes. Art installations will comprise literature, painting, video, sculpture, and any other inventive medium proposed. In most instances, the exhibit will be fabricated locally, and for some venues, the exhibit could travel to nearby host institutions if desired.

Selecting the specific art

While the *Hubble* images will, in general, be the same from venue to venue, the exhibit design will accommodate updated imagery associated with new discoveries, since the exhibit run will span several years. The local art will vary from place to place; it may be an extension of an existing local art museum for unusual or innovative art, or it can be commissioned to local professional artists. In a few venues, the art may be provided by budding student artists.

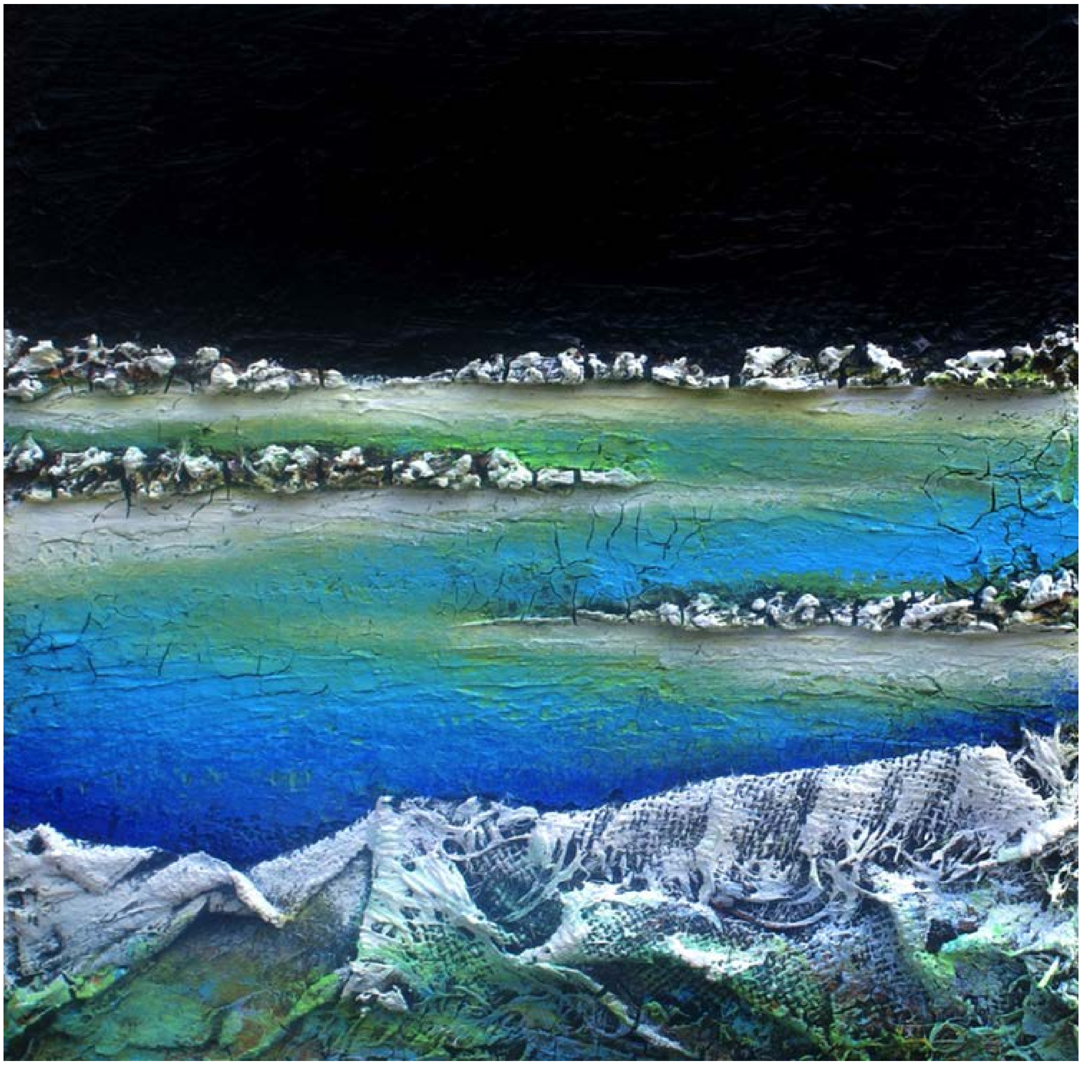

Figure 2: Art from Mario Paschetta called *Mountain Lakes* (2010) in acrylic, oils, natural earth, fabric, oxides, mortar on jute and is 150 × 150 cm. This is as an example of an art piece that might be exhibited in one of the exhibit areas, for example, in this case, the Exoplanet room.

Schedule

Our Place in Space will open in Venice in February 2017. Other locations to host their local interpretation of the exhibit are the Supernova Museum in Munich, Germany (late 2017), the Science Museum of South Australia in Adelaide, Australia (September 2017), and Vienna, Austria (2018). Other possibilities are in Edinburgh, UK, and several locations in the United States. We are excited about this world exhibit and the possibilities for its extension.

Figure 3: One of our favorite images will be displayed in the Nebula Room—the 25th anniversary image of Westerlund 2.

Executive Committee and Advisors

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Anna Caterina Bellati (Bellati Edrs.)
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Carol Christian (STScI)
Roger Davies (Oxford, UK)
Hussein Jirdeh (STScI)
NASA Representative – Ken Carpenter (NASA/GSFC)

Search

Pushing High-Contrast Imaging with *Hubble* to the Limits

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In 1980, a paper by D. W. Davies pointed out that a 2.4-meter telescope like *Hubble* could reasonably expect to detect an exoplanet in reflected light—provided that one could integrate sufficiently long to overcome the overwhelming background caused by a host star's point spread function (PSF), the diffraction pattern of a telescope created by the shape of the primary mirror, the support structure/secondary mirror, and any pupil plane aberrations (Davies 1980). More careful analysis of *Hubble*'s expected optical performance showed that the roughness of the mirror and its associated aberrations made exoplanet imaging prohibitive for even the closest of stars (Brown & Burrows 1990).

These papers, among others dating back to before the mid-1970s, constitute a history of thought on how best to detect planetary systems through imaging, spectroscopy, and photometry. By 2016, many of these fledgling ideas have come to pass, including the direct imaging of exoplanets. Currently, Fomalhaut b stands as the best candidate for the first exoplanet detected in reflected light (Kalas et al. 2013), but its unusual orbit and properties have made its planetary status controversial (Lawler et al. 2015). A handful of other Jovian-mass planets have been imaged in near-infrared light, where extreme-adaptive-optics (AO)-fed coronagraphic instrument performance and the level of emission from young planet atmospheres combines favorably for detection (i.e., Marois et al. 2008; Macintosh et al. 2015). Coronagraphic operations have also evolved extensively over the years, with new techniques developed to push to deeper contrasts through image post-processing with large imaging reference libraries (i.e., Lafreniere et al. 2007; Soummer et al. 2012).

A formal start to NASA's *Wide Field Infrared Survey Telescope* (*WFIRST*) with its Coronagraphic Instrument (CGI) will mean that discoveries using the direct imaging of exoplanets in reflected light will accelerate. CGI will suppress the PSF of the telescope at 1 part per billion at just 100–200 mas from a target star, thus allowing the direct imaging of Jupiter analogs around nearby stars.

Behind this backdrop, it may be counterintuitive to expect that the 19-year-old STIS instrument on *Hubble* can contribute to this discussion. However, recent advances in coronagraphy with STIS place it at the frontiers of high-contrast imaging science, and uniquely positioned to inform the future operations of both the *James Webb Space Telescope* and *WFIRST*.

High contrast, small angular scales

As part of the innovative calibration program 14426 "Pushing the Limits of BAR5," the STIS team asked the question: Using modern high-contrast imaging techniques developed on the ground and for *Webb*, what is the limit with which STIS can perform high-contrast imaging? To answer this question, the team selected the nearby bright star HD 33893, observed it over nine *Hubble* orbits with the STIS 50CORON aperture, placing the star behind the BAR5 aperture location (See Pushing Coronography Deeper with New Coronographic Modes; **https://blogs.stsci.edu/newsletter/files/2014/05/STISrev.pdf**).

The observing strategy was to: 1) collect as many photons as possible; 2) observe the star at multiple spacecraft orientations; and 3) and execute sub-pixel-sized dithers behind the BAR5 mask.

In a regime where the sensitivity to faint objects is determined by the PSF wings, any high-contrast observation needs enough light such that the photon noise present at a given angular separation is small when compared to the total flux of photons coming from the star. Hence, a bright star was selected to ensure plenty of counts in the PSF wings. For very bright stars, the total amount of time available to observe the star is limited by how often you read out the detector and the CCD's read-out time. For faint stars, the contrast is eventually limited by how long the total exposure time is, or by the properties of the detector.

In an ideal situation, the observations would be limited by photon noise, but additional systematic noise occurs due to non-repeatabilities with which the star is placed behind the occulter from orbit to orbit, as well as to the focus and thermal evolution of the telescope. Previous high-contrast imaging has demonstrated that changing the on-sky orientation of the scene with respect to the PSF decreases this systematic noise (Debes et al. 2013; Schneider et al. 2014), also known as Azimuthal Differential Imaging (ADI).

We also pursued sub-pixel grid dithers to mitigate pointing uncertainties that significantly degrade contrast at the inner working angle of the occulter, which were originally designed by others to aid high-contrast imaging with *Webb* (Lajoie et al. 2015). Lajoie et al. (2015) found that the combination of dithering, changing spacecraft orientations, and post-processing with the Locally Optimized Combined Images (LOCI) algorithm (Lafrenière et al. 2007) or with the Karheunen-Loève Image Projection (KLIP) algorithm (Soummer et al. 2012) can lead to gains that approach the photon limit.

With the full dataset executed by February 26, 2016, we combined all of the images and determined achieved contrast levels using both classical ADI reductions and KLIP reductions of the data. In Figure 1 we present the results of our work on program 14426. We plot the contrast levels obtained for point sources recovered with a signal-to-noise ratio of 5. We determined these curves by inserting artificial PSFs from STIS and recovering them with small photometric apertures.

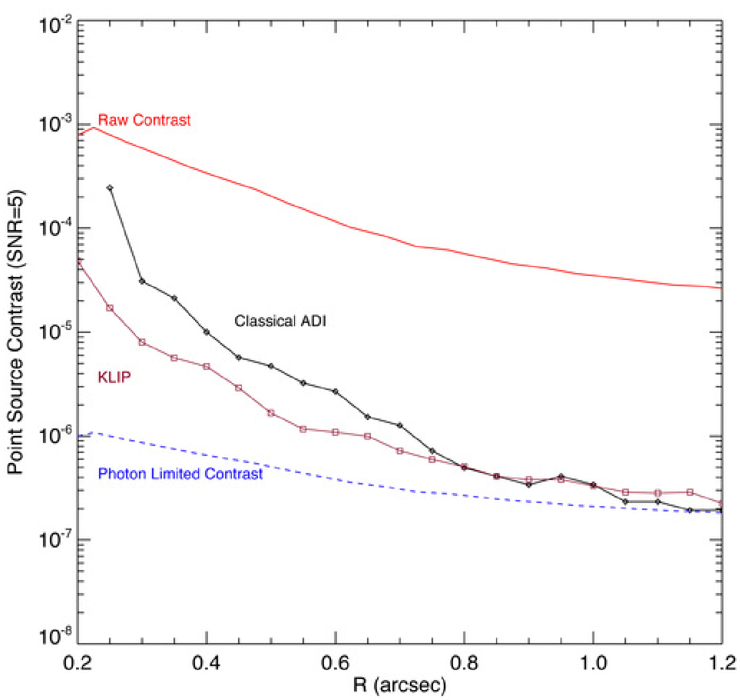

Figure 1: STIS coronagraphic contrast at small inner-working angles. This plot compares the raw contrast of the STIS corongraphic PSF wings (red curve) relative to the point source contrast achieved with Program 14426 with a classical Azimuthal Differential Imaging (ADI) reduction (black curve) and with post-processing using the Karheunen-Loève Image Projection (KLIP) algorithm (purple curve). Both results are slightly higher than the photon-limited prediction for contrast in an ideal case, but KLIP performs better than ADI interior to 0.8".

We find that we obtain 10^{-6} contrast at 0.5", and better than 10^{-6} contrast beyond 0.7", comparable or better than the best performance reported by GPI (NIR), SCExAO (NIR), and VLT/SPHERE-ZIMPOL (Visible) in the literature. We also obtain performance within a factor of a few of the photon limit estimated for the observations at these distances. The results of Program 14426 were publicized to the community through a *Space Telescope Analysis Newsletter* alert and through the STIS website (at **http://www.stsci.edu/hst/stis/strategies/pushing/coronagraphy_bar5**) on March 8, 2016. The BAR5 occulter location is now a fully supported coronagraphic aperture location within the Astronomer's Proposal Tool as of Cycle 24.

Based on these results, STIS is unique as a high-contrast imager using total intensity visible light. Particularly in the northern hemisphere, it is the only visible light coronagraph available for small inner-working angles. It also complements images taken by SPHERE-ZIMPOL, which primarily works in polarized visible light. Since GPI and SPHERE have only recently started taking observations, it will be necessary to re-assess STIS' performance relative to these instruments over the coming years.

STIS is also unique for high-contrast imaging beyond a few arcseconds, where its broad bandpass, low background, relatively large pixels, and low read-noise allow superior performance compared to the ground-based imagers. Figure 2 shows an ADI reduction of HR 8799, showing the depth one can obtain with six orbits at different spacecraft orientations with a total of exposure time of 13,800s. These images achieve point-source sensitivities of roughly V = 28.5, or 10^{-9} contrast far from the star. The field of view for STIS is significantly larger than any existing ground-based high-contrast imagers.

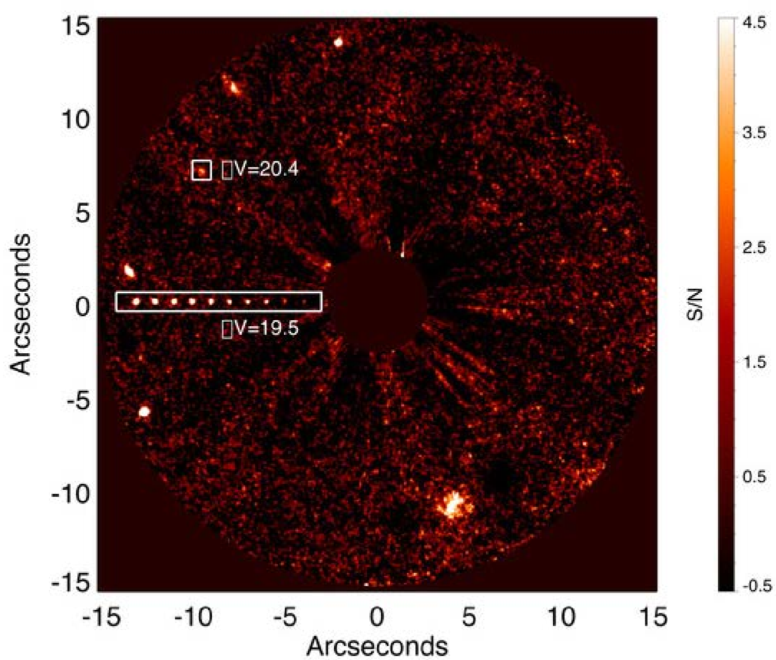

Figure 2: A deep signal-to-noise image of the surroundings to the planet hosting star HR 8799, taken as part of the GO program 12281 (PI: M. Clampin) using the WEDGEB2.5 coronagraphic position. The program used six spacecraft orientations for a total exposure time of 13800 seconds. Several background objects are easily detected, including a particularly faint object at r = 11.9" with a contrast of 20.4 magnitudes in V relative to the target star (small white box). Artificial point sources with a contrast of 19.5 magnitudes relative to the star (large rectangle) are detected down to 3.5" away from the star at a signal-to-noise greater than 5.

While the BAR5 occulter location is still relatively new, the first peer-reviewed high-contrast imaging results demonstrate its promise for the future. The nearby disk around HD 141569 was shown to have a bright inner disk at distances of 0.4" to 1.0" through STIS observations that used BAR5 (Konishi et al. 2016). The observations pushed in to an angular distance from the central star of 0.25", corresponding to a radial distance of 29 AU.

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Workshop on Feedback in the Magellanic Clouds

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The Institute hosted a science workshop from October 5–7, 2015 on *Feedback in the Magellanic Clouds*. This event focused on stellar and galactic feedback in two of our nearest dwarf-galaxy neighbors, the Large and Small Magellanic Clouds. It featured 75 registered participants, 32 posters, 13 invited talks, and a range of contributed talks and discussions.

Feedback is a mechanism by which star formation in the present affects star formation in the future. Current generations of stars release energy into the surrounding interstellar gas and sculpt the reservoir from which new stars are born. The cumulative mechanical, thermal, and radiative energy injection drives large-scale gas flows both within and out of galaxies. Feedback redistributes mass and metals around galaxies, regulates their star-formation rates, and helps to create the diverse range of morphology observed in galaxies.

The Magellanic Clouds offer an ideal opportunity to study feedback. They are nearby and spatially resolved, home to known stellar populations, surrounded by large quantities of neutral and ionized gas, and studied across the electromagnetic spectrum. The Large Magellanic Cloud is home to the giant H II region 30 Doradus (see Figure 1), which offers a close-up view into a starburst region unlike any other in the Local Group. The Magellanic Clouds allow us to study feedback on stellar, cluster, and galactic scales, giving us insight into how energy propagates from the sources where it is injected by supernovae and stellar winds, to the halos where outflows head out into intergalactic space.

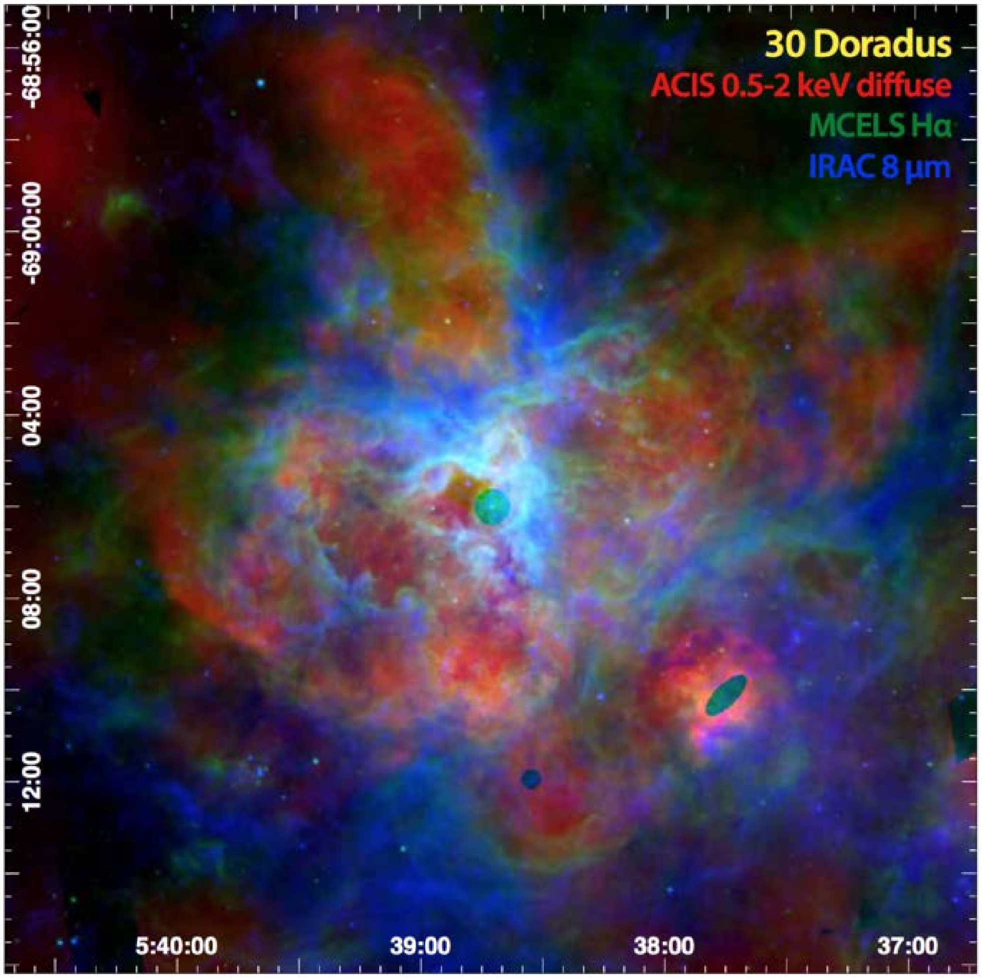

Figure 1: The 30 Doradus star-forming region in the Large Magellanic Cloud (courtesy Leisa Townsley). This image is a montage of X-ray (red, from million-degree gas), optical (green, from excited hydrogen atoms), and infrared data (blue, from dust grains). 30 Doradus is the most active star-forming region in the Local Group and provides a case study of feedback.

Starburst-driven winds are not the only means of removing gas from the Magellanic Clouds. Their mutual gravitational interaction (possibly including a past direct collision) has removed large amounts of their interstellar gas through tidal forces, creating the Magellanic Bridge and Stream. Furthermore, as the Clouds pass through the extended gaseous halo of the Milky Way, a force known as ram-pressure can also strip gas out of the Clouds. Distinguishing feedback effects from tidal- and ram-pressure effects is necessary to understand the large-scale gas morphology of the Clouds and the origin of the Bridge and Stream, and the workshop featured a discussion of these processes.

In this workshop, recent progress in Magellanic science was discussed, with a focus on feedback. Both observational and theoretical perspectives were included, as well as what we can learn about feedback in other dwarf galaxies. The Scientific Organizing Committee were particularly interested in bringing together astronomers who work on different aspects of the Magellanic system: its stars, clusters, interstellar gas, dust, and dynamics, so that new collaborations might be sparked. In our selection of invited and contributed talks, we were keen to select a speaker list that reflected gender diversity and a good balance between junior and senior astronomers, and we are confident that we met these goals. The poster session was set up to provide a relaxed environment where poster presenters had time to discuss their science with colleagues, and this was well received.

We are grateful to the event coordinator Sherita Hanna, and to the other members of the SOC (Bill Blair, Alex Fullerton, Margaret Meixner, Julia Roman-Duval, Hugues Sana, Linda Smith, Roeland van der Marel, and Nolan Walborn), who made this event possible.

Figure 2: Participants in the science workshop *Feedback in the Magellanic Clouds* assemble outside the Space Telescope Science Institute’s Muller Building on the campus of the Johns Hopkins University in Baltimore, Maryland. The event ran from October 5–7, 2015, and included 75 registered participants.

The conference webpage is at **http://www.stsci.edu/institute/conference/fimc/**.
The schedule is located at **http://www.stsci.edu/institute/conference/fimc/schedule.pdf**.
The webcast is at **https://webcast.stsci.edu/webcast/searchresults.xhtml?searchtype=20&eventid=230&sortmode=2**.

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Big Data Drives New Approaches to Doing Science

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Marc Postman, postman@stsci.edu

Big data is everywhere, and astronomy is no exception. Our ability as a society to measure ever more about consumers, take ever more pictures, and send ever more messages has been mirrored in our ability to acquire ever more digital information about the cosmos. Experiments of the next decade like Large Synoptic Survey Telescope and the Square Kilometer Array are slated to ingest an unprecedented volume of astronomical data.

The data we handle at the Institute are also arriving faster and in larger volumes—*Webb*, *TESS*, and *WFIRST* will collect much more data than our current observatories, and the Milkulski Archive for Space Telescopes at STScI is already the home the massive 2000-terabyte PanSTARRS database, recently brought into the Institute with a forklift.

Figure 1: STScI staff members (from left to right) Jeff Valenti, Andrew Fruchter, Rick White, and Armin Rest celebrate the safe arrival of the PanSTARRS storage hardware at the Institute.

Figure 2: This is what 2000 terabytes of data, loaded onto the PanSTARRS storage hardware, looked like as it arrived at the Institute.

A team of scientists, engineers, and IT experts at the Institute recently completed a study[1] of the technological and conceptual impacts of Big Data in astronomy, focusing on our current and future data holdings and addressing how astronomers can achieve the maximum scientific potential with this wealth of data. A key theme of the report is that we should see the raw volume and velocity of the data not as a limitation, but as a great opportunity for scientific discovery.

While astronomical data volumes have increased, the cost of storing, processing, and transmitting this information have decreased by much larger margins. It is thus up to us not only to build sophisticated computational systems to take advantage of faster processing capabilities, but also to implement clever methodologies and tools that provide us a deeper understanding of the physics of the cosmos from these huge data sets, and not just make smaller error bars on our existing measurements.

Figure 3: The PanSTARRS two-petabyte (2000-terabyte) storage array and its servers installed in the Institute's computing center.

The Institute's big-data study centered around a number of science cases, which pushed up against the limits of our current science computing capabilities. Some of these cases require extracting of scientific knowledge from measurements of millions or billions of images of objects in the universe. These images hold huge amounts of untapped information about dark matter (via gravitational lensing), galaxy evolution, and star formation. It is difficult to gain detailed scientific understanding from these images, both because the data volume is so large, and because we fundamentally do not know how to best classify and measure such images. One way forward is to harness Machine Learning and Deep Learning methodologies that use data-driven approaches to find the most information-rich aspects of images.

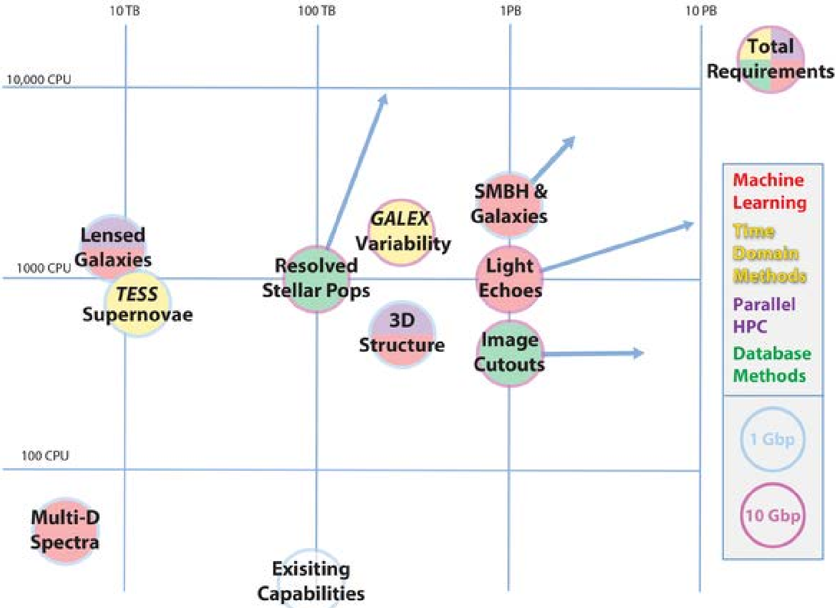

Figure 4. The science cases discussed in the report. Each case requires some disk space (x-axis) number of CPU (y-axis) new methodologies (fill colors), and bandwidth (outline color). The arrows indicate possibilities for growth. Our existing capabilities and the integrated requirements to perform all these projects are also shown.

Data-intensive imaging tasks are not limited to objects with observed shapes. Future missions like *WFIRST* will sample tens of millions of stars in a single day, allowing us to understand the detailed history of star formation across many galaxies. To process these resolved stellar populations will require both increased computational infrastructure and more deeply integrated databases.

Future missions will also survey billions of galaxies, whose redshifts we need to measure, or whose low-resolution spectra we need to characterize. The process of computing redshifts from imaging (a.k.a. photometric redshifts) for so many galaxies is computationally intensive, but also may require interaction from users, who will want to tune the redshift-determination procedure to meet specific scientific needs. Spectral characterization will also need to be optimized and automated. Developing a "science as a service" approach, in which users within and beyond the Institute can run specific computationally intensive tasks through application programming interfaces, became a central proposal of the report.

Time domain observations may also require significant computational resources, as well as new methodologies. For example, the *GALEX gPhoton* database, which has over 1 trillion records of time-tagged photon arrival events, could allow us to find all sorts of new variable phenomena, but requires immense processor power in a distributed and integrated computer environment to perform many searches simultaneously. Light echoes—reflections of supernovae explosions bouncing through our Galaxy—require not only accessing petabyte-scale image databases, advanced image classification algorithms, and light-ray tracing over the time domain, but may also require serving imagery to citizen scientists for inspection, putting higher performance requirements on our network bandwidth capacity.

All of these advanced scientific investigations will not only require silicon and copper, but will also require our staff to rethink data itself as a priority. One of the key recommendations of the report is that the Institute should establish a Data Science Mission Office (DSMO), elevating our astronomical archives (MAST) and computational infrastructure to the same level as *Webb* and *Hubble*. The Institute has moved to establish DSMO this year, and with it, our commitment to exploring the universe as much with our computers, algorithms, and data, as with our telescopes.

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[1] The full report is available at **http://archive.stsci.edu/reports/BigDataSDTReport_Final.pdf**

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The *Hubble* Spectroscopic Legacy Archive (HSLA)

Andrew Fox, *afox@stsci.edu*, Jason Tumlinson, *tumlinson@stsci.edu*, and Molly Peeples, *molly@stsci.edu*

Introduction

Data archiving is a crucial component of the operation of an astronomical observatory. Archives ensure the legacy of the observatory, and act as multipliers for its science output, by enabling science investigations unrelated to those in the proposals that obtained the data. To maximize their use by the community, archives need to be well populated, easy to use, and designed so that astronomers can quickly determine which targets of a given type have been observed. In this *Newsletter* article we discuss a new archival resource for spectroscopic data from the *Hubble Space Telescope*, named the *Hubble* Spectroscopic Legacy Archive (HSLA), hosted at the *Hubble* Archive at the Institute.

With no future space ultraviolet instruments currently planned, the data from the UV spectrographs aboard *Hubble* have an important legacy value beyond their initial science goals. The HSLA is an effort designed to maximize the longevity of the UV spectroscopic data and to accelerate the scientific study of these data. The HSLA is led from the Institute with involvement from several spectroscopists in the community (see Table 1). The HSLA working group was formed following a workshop held at the Institute in November 2012, *Enhancing the Legacy of HST Spectroscopy*, chaired by Alessandra Aloisi and Stefano Casertano, in which community input was given on the needs for archival products for spectroscopy, and the Institute began planning the tools and products necessary to meet these needs.

Table 1: HSLA Working Group Members

The first release of the HSLA

The first release of the HSLA was issued in February 2016. This release contains uniformly reduced, co-added, and classified spectra for all *COS* far-ultraviolet (FUV) observations publicly available at that time. It contains over 11,000 individual exposures on 1,414 distinct targets. The data are packaged into “smart archives” according to target type and scientific themes (such as "solar system," "early type stars," "white dwarfs," and "starburst galaxies") to facilitate the construction of archival samples for new *Hubble* proposals and for general science usage. This release was timed to provide a resource for astronomers preparing Cycle 24 *Hubble* proposals with a Phase I deadline of April 8, 2016. The HSLA products are described and available for download at *https://archive.stsci.edu/hst/spectral_legacy/*

As well as providing quick access to the raw and reduced data, and tables sorted by target type, the HSLA offers several additional features. A "quick look" capability plots the co-added spectra and allows users to assess data quality (see Figure 1). A demographic section shows the distribution of instrument modes and programs used to observe a particular target. A light curve shows the variation of the source flux with time, allowing for an assessment of time-variability at different wavelengths.

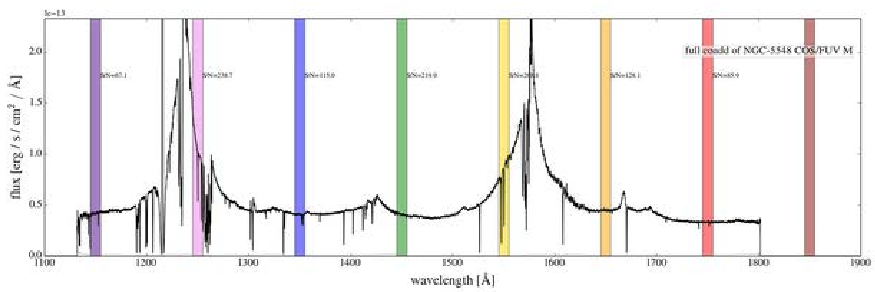

Figure 1: Co-added spectrum of the AGN NGC 5548 generated by the HSLA, showing flux against wavelength for all data obtained using the COS G130M and G160M gratings. The eight colored stripes show the wavelength regions used to measure the signal-to-noise ratio of the data.

How the HSLA co-addition works

One of the key concepts behind the HSLA is combining spectra across exposures, visits, and programs to give a single co-added spectrum per target. This approach is appropriate for many scientific uses, especially for non-time-variable sources that have been observed on multiple occasions. For COS/FUV observations, two medium-resolution gratings are available (G130M and G160M) and one low-resolution grating (G140L). The HSLA presents the medium-resolution and low-resolution products separately; it does not combine across different resolutions. Figure 2 shows the distribution of usage across COS gratings.

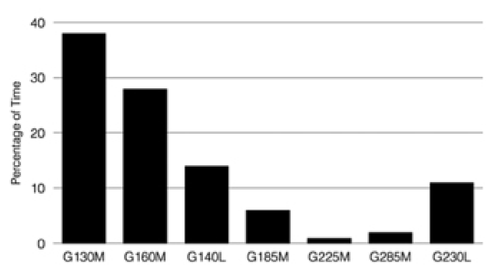

Figure 2: Percentage of COS usage broken down by grating, for all data taken since installation in 2009. The medium-resolution FUV gratings G130M and G160M are the most widely used.

The extracted one-dimensional spectra produced by the CalCOS data reduction pipeline (known as x1d.fits files) are taken as inputs to the HSLA. The co-addition code is a python script that passes through several steps, described in full in the documentation on the HSLA website. In brief, for each target the code decides which files to combine based on the file headers, applies wavelength shifts to align interstellar absorption lines, applies a nearest-neighbor algorithm to sample the spectra onto a single wavelength grid without any attempt to interpolate between adjacent pixels, then co-adds the counts from each exposure. This process preserves the statistical independence of the signals in each pixel. The code then subtracts the background level, uses Poisson statistics to calculate the uncertainties on the counts, then converts to flux at the end.

The HSLA going forward

A preliminary version of the HSLA was released at the January 2016 AAS meeting in Kissimmee, Florida. Institute astronomers gave demonstrations on how to use the HSLA (see Figure 3), and distributed USB sticks loaded with all the co-added COS FUV data to astronomers who attended the demonstration. Future releases of the HSLA will contain co-added COS/NUV data and *STIS* UV data, and will update the COS/FUV data products for any changes to the CalCOS calibration pipeline, such as improvements to the wavelength-scale dispersion solution and changes to the reference files.

Figure 3: Demonstration of the HSLA at the January 2016 AAS meeting in Kissimmee, FL. given by Institute astronomer Molly Peeples.

Questions about the content of the HSLA can be sent to _hst_spec*legacy@stsci.edu*. The HSLA makes use of Spectator, an open-source python code written by Molly Peeples, to create its plots of demographics and spectra. Spectator is available on *GitHub*.

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Wide Field Infrared Survey Telescope (*WFIRST*) Starts Mission Formulation Phase

Roeland P. van der Marel, *marel@stsci.edu*

The *Wide Field Infrared Survey Telescope* (*WFIRST*) got its formal start in February 2016, when NASA advanced it into the mission Formulation Phase, with launch aimed for the mid 2020s. This marked the completion of several years of pre-formulation work, capped by a successful Mission Concept Review in December 2015.

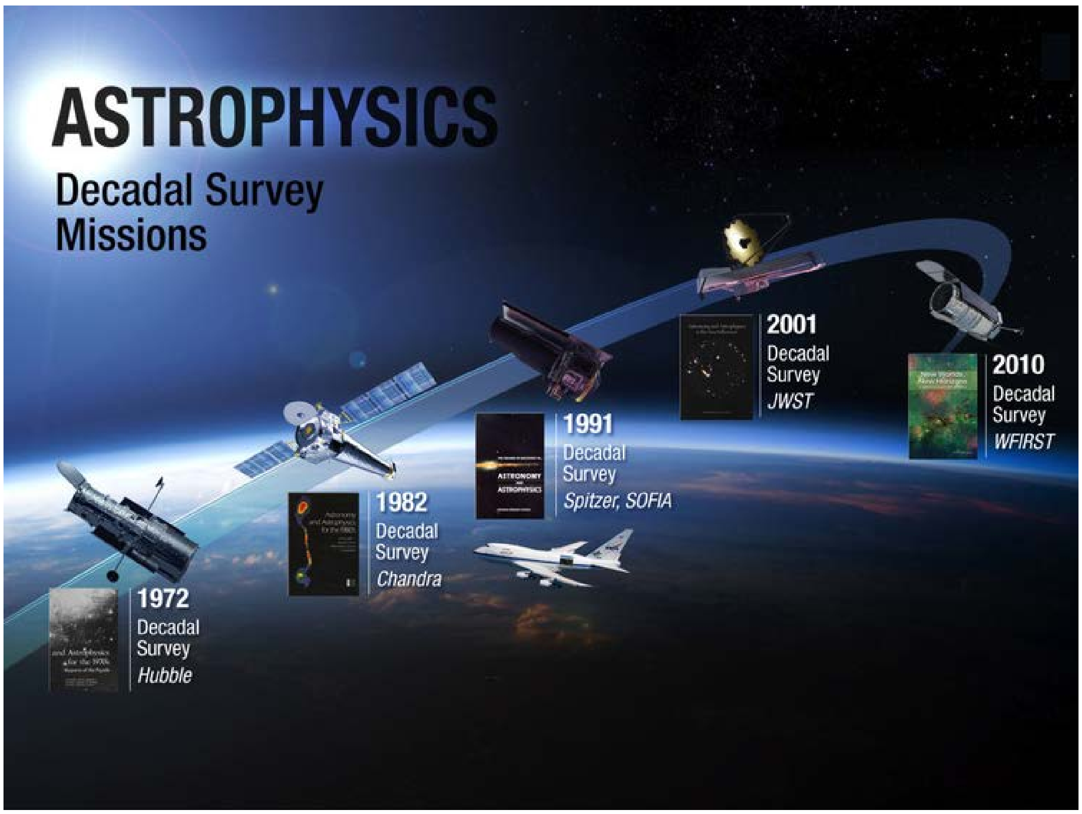

Figure 1: *WFIRST* will be the next mission after *Webb* in a long line of successful large NASA space missions recommended by the Decadal Surveys in Astronomy and Astrophysics.

WFIRST was the highest ranked large space mission in the 2010 Astronomy & Astrophysics Decadal Review. It will provide fundamental new constraints on dark energy, a repulsive force that is pushing the universe apart at an ever-faster rate; on the large-scale distribution of dark matter, which is most of the matter in the universe; and on the demographics and properties of exoplanets, which are planets around other stars. It will also build on *Hubble*'s legacy by providing major advances in all areas of astrophysics through competed Guest Observer and funded archival Guest Investigator programs.

While originally envisioned to be a 1.5-meter telescope, the *WFIRST* concept now makes use of an existing optical telescope assembly with a 2.4-meter-diameter primary mirror. This "AFTA" (Astrophysics-Focused Telescope Assets) telescope was donated to NASA in 2012 by the National Reconnaissance Office. The observatory design, instrument capabilities, and observing programs may all continue to evolve as the mission matures. However, the present mission concept clearly shows *WFIRST*'s potential for revolutionizing many areas of science.

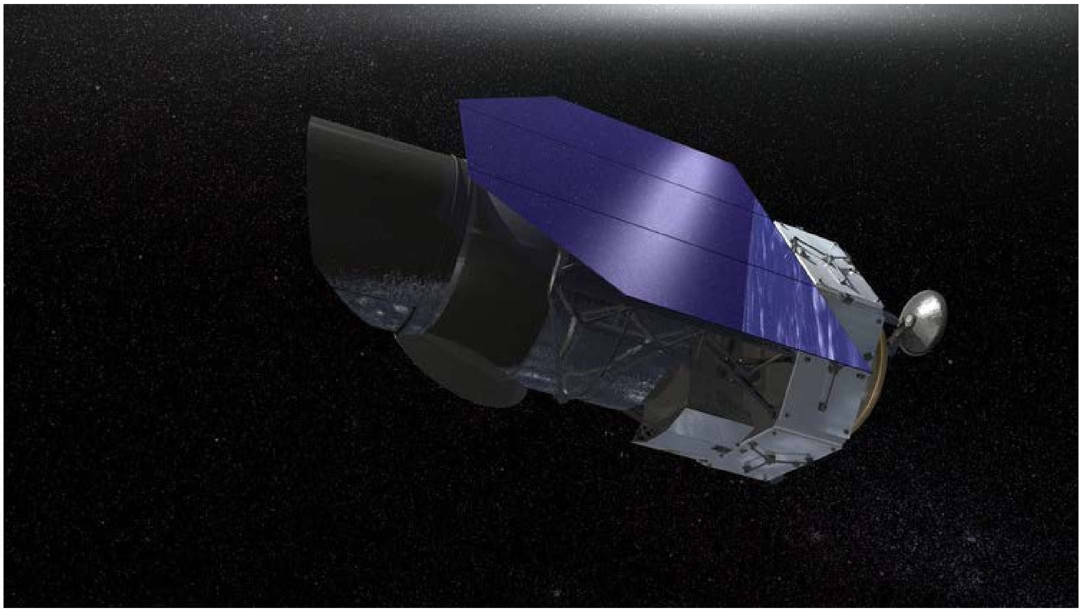

Figure 2: The *Hubble*-sized *WFIRST* is now in the NASA mission Formulation Phase, with launch aimed for the mid 2020s. The Institute will be a partner in the mission science operations, and will lead the systems for the Wide Field Instrument, dark energy surveys, mission scheduling, and data archive.

The observatory will have two instruments to execute its science program, a near-infrared imaging camera and a visible-light coronagraph. The prime mission will be six years, but mission consumables will be sized to enable a potential extended mission phase.

The Wide Field Instrument (WFI) will operate in the near-infrared 0.7–2.0 micron range. Eighteen 4k × 4k detectors will yield an unprecedented field of view, 100 times that of *Hubble*. This will allow *WFIRST* to produce large-scale maps of the night sky at *Hubble* resolution. The present WFI concept has 6 imaging filters, a grism, and an Integral Field Channel (IFC).

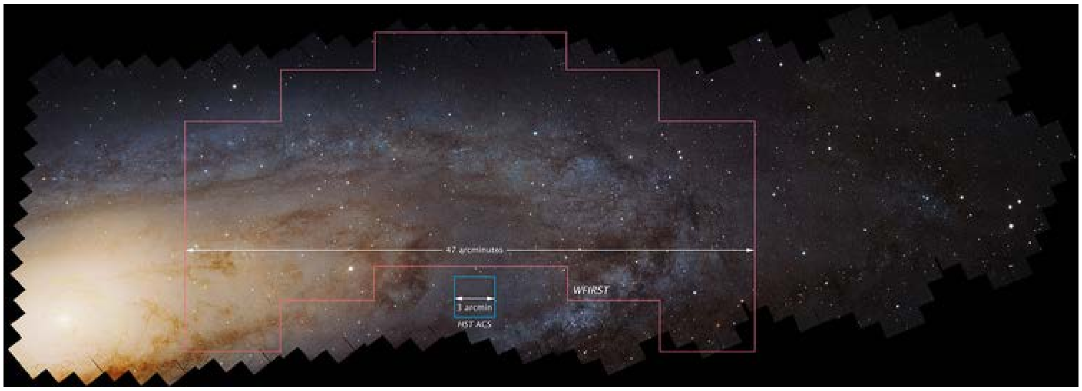

Figure 3: Overlay of the *WFIRST* field of view on top of a mosaic of the Andromeda galaxy. The mosaic was created from over 400 individual pointings obtained by the Panchromatic *Hubble* Andromeda Treasury (PHAT) program. A single ACS/WFC field of view is shown for comparison. By contrast, the *WFIRST* Wide Field Instrument, with its 18 4k × 4k near-IR detectors, will be able to image most of this field in just one pointing. This potential for wide field surveys at space-based resolution will allow *WFIRST* to revolutionize many areas of astrophysics.

Three large surveys will be executed with the WFI: a High-Latitude Survey (2 years) and a Supernova Survey (0.6 years) for studies of dark energy and the large-scale structure of the Universe; and a Bulge Microlensing Survey (1 year) to complete the census of exoplanets in a mass-radius regime that is complimentary to that surveyed by the *Kepler* mission.

The High-Latitude Survey will cover over 2,200 square degrees with imaging and low-resolution (grism) spectroscopy. The imaging, in four NIR bands (Y, J, H, and $F184$), will reach $J = 26.7$ AB for point sources. The spectroscopy will measure redshifts for over 15 million sources at redshift 1.1 to 2.8.

The Supernova Survey will have both imaging and IFC spectroscopy. The imaging survey is designed in three tiers, shallow, medium, and deep, to find supernovae at redshifts below 0.4, 0.8, and 1.7, respectively. The three tiers will cover approximately 27, 9, and 5 square degrees, respectively, with observations repeated with a cadence of 5 days, in filters Y and J for the shallow tier, and J and H for the medium and deep tier. IFC spectrophotometric observations will be used to fully characterize the type and light curve of a subset of 2700 supernovae, chosen to sample the full redshift range.

These surveys will measure the equation of state of dark energy and its time evolution, helping determine whether it is a cosmological constant, through all of the major methods suggested thus far. The HLS will enable weak lensing shape and photometric redshift measurements of hundreds of millions of galaxies, which will in turn yield precise measurements of distances and matter clustering through measurements of cosmic shear, galaxy-galaxy lensing, and the abundance and mass profiles of galaxy clusters. The wide-area HLS grism survey will determine million of redshifts for galaxies between $z = 1$ and 3, thus measuring the evolution of the size of the Universe and constraining the scale of Baryon Acoustic Oscillations to 0.3%, as well as measuring the growth of structure via redshift-space distortions. The SNS will constrain dark energy by discovering and measuring precise distances to thousands of Type Ia supernovae up to redshift $z = 2$.

In the Bulge Microlensing Survey, ten fields (an area of over 2 square degrees) will be imaged every 15 minutes over contiguous 72-day periods, to create highly-sampled light curves of 56 million stars brighter than H = 21.6 (AB). Six such campaigns will be executed over the mission lifetime, resulting in the expected discovery, through their microlensing signature, of over 2000 bound planets in the range 0.1–1000 Earth masses, including about 400 of Earth mass and below. These planets will sample orbital major axes from 0.03 to 30 AU, including the habitable zone, the outer regions of planetary systems, and free-floating planets. Another 20,000 giant planets in short-period orbits will be detected from their transit signatures.

All of these surveys will yield a treasure trove of data for Archival Guest Investigator studies in other areas of astrophysics. Examples of science projects enabled by the data in the High-Latitude Survey include: mapping the formation of cosmic structure in the first billion years after the Big Bang via the detection and characterization of over 10,000 galaxies at $z > 8$; finding over 2,000 QSOs at $z > 7$; quantifying the distribution of dark matter on intermediate and large scales through lensing in clusters and in the field; identifying the most extreme star-forming galaxies and shock-dominated systems at $1 < z < 2$; carrying out a complete census of star-forming galaxies and the faint end of the QSO luminosity function at $z \sim 2$, including their contribution to the ionizing radiation; and determining the kinematics of stellar streams in the Local Group through proper motions.

Moreover, 25% of the primary mission (1.5 years) is set aside for Guest Observer studies. Observations will be competitively selected through peer review, in the same spirit as for other NASA Great Observatories. These programs can use any of the available instruments and modes to study topics in any area of astrophysics. Examples include: studying young clusters and embedded star-forming regions within the Galaxy; reaching the very faint end of the stellar luminosity function via very deep observations of Local-Group galaxies; or mapping the core of the Virgo cluster.

The second *WFIRST* instrument is the Coronagraph Instrument (CGI), which is specially designed for studying planets orbiting other stars. It will use deformable mirrors to reach groundbreaking new contrast levels of around 1 in a billion, several orders of magnitude better than the current state of the art with ground- and space-based observatories. It will operate in the 0.4–1.0 micron range, and will have both an imaging detector for exoplanet detection, and an IFC for exoplanet spectroscopy. The associated technology development may also pave the way for future missions aimed at detecting signs of life in the atmospheres of Earth-like exoplanets.

The CGI can measure planets similar to those in our Solar System, and also measure for the first time the photometric properties of the 'mini-Neptune' or 'super-Earth' planets—objects that *Kepler* has shown to be the most common planets in our galaxy, but with no analog in our own Solar System. With a 1-year program, dozens of exoplanets can be targeted with the CGI. Initial observations will focus on discovery and characterization of planets around pre-selected target stars. When a previously known or unknown planet is detected, additional observations will be made for longer time periods, with full spectral resolution for planet characterization.

Figure 4: *WFIRST* has an ambitious science program. This includes a multi-pronged approach to measuring dark energy, the discovery and census of planets down to sub-Earth masses via their microlensing signatures, and the imaging and spectroscopy of planets via coronagraphy. Moreover, the *WFIRST* instruments will enable many exciting studies in general astrophysics, through the combination of Guest Observer programs and archival Guest Investigator studies of the wide-area and time-resolved *WFIRST* surveys.

NASA competitively selected eleven Science Investigations Teams and two Adjutant Scientists for the *WFIRST* mission. The leading members of these teams, together with NASA and Science Center representatives, make up the Formulation Science Working Group. This group will advise the Project on mission, observation, and analysis concepts, systems and designs that will optimally enable *WFIRST* to meet its science goals.

The *WFIRST* mission will provide tremendous synergy with *Hubble* and *Webb*. It will extend the legacy of *Hubble*-quality imaging to much wider fields, and is expected to find many unique objects suitable for detailed follow-up study by *Webb* (which will have enough propellant to remain active throughout the 2020s). For example, *WFIRST* survey discoveries might include rare early galaxies and bright supernovae explosions from early generations of stars. *Webb* observations using multi-band, high-resolution imaging and sensitive infrared spectroscopy can reveal the detailed nature of such sources.

Work on the *WFIRST* mission is a collaboration among several different partners. The *WFIRST* Project Office is at Goddard Space Flight Center (GSFC), which also oversees the work on the WFI instrument, the Spacecraft Bus, and System Integration, and which will host the Mission Operations Center. The Jet Propulsion Laboratory (JPL) is developing the CGI instrument. *WFIRST* Science Operations will be a shared responsibility between GSFC, the Institute, and the Infrared Processing and Analysis Center (IPAC).

The Institute science operations responsibilities will include the mission's observation scheduling system, data archive, dark energy survey products, and WFI data processing system. The Barbara A. Mikulski Archive for Space Telescopes (MAST) at the Institute already holds the astronomical data from some 20 astronomy missions, and the addition of the *WFIRST* data will add considerably to its scientific discovery potential. The IPAC science operations responsibilities will include the proposal peer-review process, microlensing survey products, and CGI data processing system. GSFC will provide overall science operations management and strategic guidance.

Institute work on the *WFIRST* science operations planning will build on expertise with similar instruments and modes on *Hubble* and *Webb*. Work in prior years has focused on a range of activities. We have released software simulation tools, building on synergy with ongoing *Webb* development, to help astronomers assess what the Universe looks like through the eyes of *WFIRST*. For example, *Webb*PSF calculates the field-dependent point spread function, while Pandeia simulates small galactic or extragalactic scenes. We also published technical reports on a range of topics, including mission scheduling and guiding, and the operations and data analysis for the coronagraph and wide-field grism modes.

Institute tools and results are being distributed through our *WFIRST* web site (**http://www.stsci.edu/wfirst**), which is part of our broader efforts to engage the astronomical community in this exciting new mission. Other *WFIRST* information is available on the mission websites of our partners at GSFC (**http://wfirst.gsfc.nasa.gov/**) and IPAC (**https://wfirst.ipac.caltech.edu/**).

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AAS 228 June 2016, San Diego

Collated on behalf of STScI by C. Christian, *carolc@stsci.edu*

The Space Telescope Science Institute will be at the 228th AAS meeting in San Diego, California, with an exhibit booth showcasing the missions we support for the science community, several technical presentations in instrument sessions, a wide variety of science presentations, and press releases.

Exhibit booth

Institute staff representing the *Hubble*, *Webb*, and *WFIRST* missions will be available at the Institute's booth to provide information on new developments and updated status of these missions, and to describe our upcoming initiatives for user community support. Staff scientists and engineers will discuss improvements in calibration and new modes for *Hubble* instrumentation to support ever-more ambitious science. Attendees can obtain information on upcoming releases of user tools and software to help the community plan the first *Webb* observations, and the development of simulation capabilities related to the *WFIRST* mission.

Institute experts will demonstrate the Mikulski Archive for Space Telescopes (MAST) portal and the new *Hubble* spectroscopic archive as well as new software products for data analysis. A new website and modern 3-D exposure time calculator for *Webb*, and Point Spread Function (PSF) and image simulations for *WFIRST* will also be shown.

Hubble observers will be interested in more details about the successful new mid-cycle proposal process and what types of observations are appropriate for the program. Similarly, future *Webb* users will be very interested in the science timeline and upcoming call for proposals for the Early Release Science program. There will be new handouts on these topics available at the booth. In addition, attendees should check back often for specialized focused discussions on our large touch-panel screen and additional hands-on demonstrations from our missions.

Figure 1. This is the backdrop for the Institute's booth, where staff representing the *Hubble*, *Webb*, and *WFIRST* missions will provide information on new developments and updated status of these missions. They will also describe the Institute's upcoming initiatives for user community support.

Experts from our Office of Public Outreach will also be on hand to discuss new opportunities for scientists to become involved in E/PO initiatives, and to explain our augmented reality tool for use with hand held devices.

Observatory Technical Information: What to Watch for in Sessions

What's new with the Cosmic Origins Spectrograph (*COS*)?
Find out details on time-dependent sensitivities of the FUV detector and the effect of hot spots as well as new wavelength calibrations.

A Review of 14 Years of Observations with the Advanced Camera for Surveys (*ACS*).
New calibrations of the repaired ACS Wide-Field Channel (WFC), having operated more time in repair mode than in its original launch configuration, allow continued high productivity with this camera. Find out the new techniques used to support prime and parallel programs.

All about the Workhorse Wide Field Camera 3 (*WFC3*).
Now it its sixth year of operation, new WFC3 software is available to address ultraviolet/visible (UVIS) Charge Transfer Efficiency (CTE) loss due to radiation damage, and new dark calibrations improve usability. Improved photometric and flat-field calibrations accompany new astrometric solutions and PSF calibrations for the UVIS. Also, hear and discuss how infrared (IR) channel data processing and methods to address persistence assist deep imaging, and new calibrations address IR photometric performance.

Getting in Touch

The Institute's website is: **http://www.stsci.edu**.

Assistance is available at *help@stsci.edu* or 1-800-544-8125.

International callers can use 1-410-338-1082.

For current *Hubble* users, program information is available at:
http://www.stsci.edu/hst/scheduling/program_information.

The current members of the Space Telescope Users Committee (STUC) are:

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Rupali Chander, University of Toledo
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