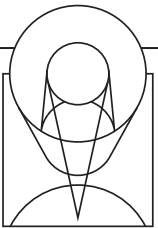


30 Doradus Nebula
Credit: NASA, ESA, and E. Sabbi (STScI)

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NEWSLETTER

Space Telescope Science Institute

Towards a 2020 Vision for the *Hubble* Space Telescope

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As we approach the 25th anniversary of the launch of the *Hubble Space Telescope* on April 24, 1990, it seems appropriate not only to look back at *Hubble's* achievements, but also to look forward to what is yet to come. There will be plenty of opportunities to reminisce in the coming months, so let's turn to *Hubble's* future. Indeed, *Hubble* has always been about bringing the future a bit more into focus—forward leaning, pushing the envelope, blazing frontiers, and opening new horizons to curious minds everywhere.

Long before the start of the mission, someone coined a phrase that captures the essence of *Hubble's* ability to surprise—"conscious expectation of the unexpected." That philosophical approach underlies the concept of NASA's Great Observatories, *Hubble*, *Chandra*, *The Compton Gamma Ray Observatory*, and *Spitzer*: broad-based missions that go beyond focused experiments. It still serves well as a reminder that being open to new lines of research—ones we cannot yet envision—is just as important as planning the next steps along known lines. With this in mind, the Institute and the *Hubble* project at Goddard Space Flight Center use a five-year window to set priorities for technical work and observing initiatives. Maximizing the science from the observatory and its archives is always the top goal, of course. And this is where you come in—we want your help in shaping *Hubble's* legacy. How can you help? We'll get to that in just a bit.

Hubble 2020 Vision Statement

Operate the *Hubble Space Telescope* until 2020 or beyond so that there is at least one year of overlapping science observations with the *James Webb Space Telescope*, performed in a manner that maximizes the science return of both observatories, takes full advantage of *Hubble's* unique capabilities, addresses the astronomical community's scientific curiosity, and engages the public and students in scientific discovery.



In the past, a five-year timescale roughly coincided with the interval between *Hubble* servicing missions, and it was not surprising that each upgrade of the observatory spurred an evolution of technical and scientific goals. Because Servicing Mission 4 is now over five years behind us—and because the launch of the *James Webb Space Telescope* is now less than five years away—it makes sense to take an inventory of what we have learned, and, with *Webb* firmly in mind, to refresh our thinking about *Hubble*'s future.

Hubble's power to revolutionize has never been greater than now. The instruments are calibrated better than ever, and we are using them in ways we had not anticipated at the time of the last servicing mission. For example, with the new spatial scanning mode for Wide Field Camera 3, it is possible to achieve very high differential photometric precision (~30–50 ppm) on exoplanet transit depths, and to achieve relative astrometric measurements of a few tens of *micro* arcseconds. These capabilities exist today because of our dialog with astronomers wishing to push *Hubble* even further than had been thought possible. Consider also the performance of “ordinary” imaging or spectroscopic observations. Astronomers worldwide can propose for sharp, deep, and stable images, or for different flavors of spectra, from the ultraviolet to the near infrared, from 110 nm to 1.7 microns. Such observing power is unique, and will remain so for the foreseeable future.

Shortly, *Webb* will complement *Hubble*, adding the infrared wavelength region. *Webb* will produce comparable pictures and multi-object spectra of the universe between 600 nm and 28 microns—overlapping *Hubble* at very near-infrared and long-optical wavelengths. When both observatories are operating, we expect strong demand for *Hubble* observations of *Webb* objects and vice-versa. Both observatories will make discoveries that only the other can investigate further. This will be synergism writ large.

We expect many more years of robust operation for *Hubble*. Past hardware problems have typically involved either electrical issues in the science instruments or mechanical failures of the gyros. Most of *Hubble*'s subsystems have considerable redundancy, including the science instruments. For example, the Wide-Field Camera 3 and Cosmic Origins Spectrograph both have dual-string electronics. Also, due to prudent investments in engineering and the ground-system over the past decade, we can now operate *Hubble* with only *one* gyro, if needed.

In 2013, NASA formally analyzed subsystem lifetimes and found that the observatory should remain highly capable for the remainder of this decade—assuming that we continue to mitigate the degradation and failure modes of the hardware. If these investments are adequately funded, there is every reason to believe that *Hubble* will sail through the anniversary in 2020 with flying colors.

Preparing for the coming epoch of scientific reciprocity between *Webb* and *Hubble* is a top priority for the Institute and the *Hubble* project. The scientific potential and operational synergies of these two “great observatories” are so deeply intertwined that we have given this effort its own vision statement!

We expect *Hubble* and *Webb*—separately and together—to address the top scientific questions of 2020, which will surely include:

- What are the properties of planetary systems around other stars? It is now clear that there is a tremendous variety of planetary systems, many, perhaps most, quite different than our own. Understanding these systems may very well provide clues to our own origins.
- When did the first stars and galaxies form? *Hubble* is pushing closer than ever to the beginning of galaxy formation through its Frontier Fields initiative, but *Webb* will push back in time even further and increase the sample. Together, the two observatories will trace stellar and galactic evolution over the entire age of the universe.
- What is dark energy? This is one of the most interesting questions in all of physics, and we're just beginning to formulate the paths toward an answer.
- How does dark matter affect the evolution of galaxies? Observing dark matter, or more properly the effects of dark matter on ordinary matter or light, requires a multi-pronged approach that requires multi-wavelength data and a combination of spectroscopic and imaging information. *Hubble* and *Webb* have unique capabilities that together can be used to study dark matter on scales ranging from the sizes of stars to clusters of galaxies.
- How and where do black holes form? Peering into the hearts of galaxies and stellar clusters, both *Hubble* and *Webb* provide unique information about the motions of gas and stars used to constrain the black hole masses. Both observatories are well suited to studying the host environments and investigating the sources of matter fueling black holes.
- How are the chemicals of life distributed in the universe? *Hubble* has taught us much about the cycles of matter and energy in environments of all types, and *Webb* will expand that knowledge. These are complex processes requiring a multitude of observational inputs to understand the chemistry, physics, and dynamics affecting the fate of chemical compounds.

So what's new? The *overlap* between *Hubble* and *Webb* in the 2020 timeframe is *really new*. It will magnify and multiply their separate forces for research. The union of *Webb* and *Hubble* will further signify a time in astronomy without precedent. Indeed, the sheer magnitude of opportunities in the *Hubble–Webb* era cannot be easily summarized. Here are just a few examples of synergistic programs:

- The atmospheric composition of planets around other stars is a field of intense study with *Hubble*, and will be a primary research area with *Webb*. As new exoplanets are discovered by *Kepler*, the *Transiting Exoplanet Survey Satellite*, and other observatories, studies by *Hubble* and *Webb* combined will yield fresh insight into how planets—perhaps even earth-like planets—form and evolve.
- *Hubble* is currently exploring the cosmic frontier at redshifts of $z \sim 9$ –10, corresponding to times when the universe was only a few hundred million years old. *Webb* will explore beyond this time horizon, approaching the Big Bang—and the beginning of time—ever more closely. *Hubble* will identify candidate fields for *Webb*, and will follow-up *Webb* discoveries with new, tailored observations of particular fields.
- *Webb* will study star-forming regions in great detail. To complete the census of these stellar nurseries, and to investigate newly discovered protoplanetary systems, *Webb* findings will call for complementary *Hubble* observations at optical and ultraviolet wavelengths.
- Throughout its lifetime, *Hubble* has monitored weather and climate on planets in the solar system. In the *Webb* era, new observations will extend the time coverage and increase the diagnostic power by probing more deeply into the atmospheres of the giant planets. Combined, the two observatories will essentially provide a “3D” view of these atmospheres.
- *Hubble* provides unique insight into the properties of individual stars and the aggregate stellar populations of stellar clusters and galaxies of all types. Reconstructing the star-formation histories of nearby galaxies with complementary *Hubble* and *Webb* observations will place studies of distant galaxies and metal enrichment on a solid foundation. Follow-up studies of rare types of stars will likely also be useful for understanding the ages of some stellar populations.

There will be no lack of exciting science for *Hubble* to pursue—before *and after Webb* is launched. Indeed, the amount of *Hubble* observing time proposed is typically six times more than is available. There is clearly no shortage of good ideas—but that has always been true. The two new factors are *Hubble*'s finite lifetime—no more servicing missions are planned—and the synergism with *Webb*.

The 2020 Vision is a rallying point for *Hubble* stakeholders to strategically plan for the opportunities, issues, and trade-offs of the *Hubble–Webb* era. We intend it to be a framework for ensuring that *Hubble* remains at the forefront of astrophysics well beyond its 25th anniversary.

The 2020 Vision embraces the principles that have made the mission so successful: operations guided by science, partnership with other NASA missions, a fair time-allocation process that gives top priority to demands for *Hubble*'s unique capabilities, and public outreach, which shares the excitement of scientific discoveries with the public and students. Implicit in the vision is a commitment to maintain a healthy grant program so that the astronomical community continues to be active and engaged in *Hubble*'s success.

The Institute is soliciting white papers from the community about how best to structure *Hubble*'s science program in its remaining years. Suggestions might include new observing initiatives akin to the *Hubble* Frontier Fields or Treasury programs. Perhaps we need a new proposal category for *Hubble* to prepare for *Webb*, or a reciprocal observing agreement with *Webb*, like that already in place for *Chandra*, *Spitzer*, *XMM-Newton*, and the National Radio Astronomy Observatory. Perhaps we need new ways to structure the *Hubble* time-allocation process in the years that overlap with *Webb*.

These possibilities will be under discussion—and more, including ones that you might suggest. Put on your thinking caps. What do *you* want *Hubble*'s future to look like? We hope that you will send us your thoughts in response to the white paper call and help us shape *Hubble*'s 2020 Vision.

Hubble Cycle 22 Proposal Selection

Jennifer Lotz (lotz@stsci.edu), Brett Blacker (blacker@stsci.edu),
Claus Leitherer (leitherer@stsci.edu), and Neill Reid (inr@stsci.edu)

Hubble Space Telescope embarked on its 22nd cycle of science observations in October 2014. The scientific demand for *Hubble* data remains high and diverse, with this cycle receiving slightly more proposals than Cycle 21—the second-largest number of proposals for any *Hubble* cycle. In April 2014, the Institute received 1134 Cycle 22 proposals requesting ~19,900 orbits. The proposals included 122 archival proposals and 78 theory proposals. Co-investigators were drawn from 45 U.S. states, 44 countries, and 6 continents.

The *Hubble* Time Allocation Committee (TAC) reviewed the proposals in June 2014, and recommended the allocation of 3707 *Hubble* orbits to 263 programs. The selected programs span a broad range of science questions, from the *New Horizons* search for Kuiper Belt asteroids (PI J. Spencer) and the study of exoplanet atmospheres (PI K. France), to improved measurements of the Hubble Constant (PI W. Freedman) and detection of the brightest galaxies in the early universe (PI M. Trenti).

Review Process

The *Cycle 22 Call for Proposals (CP)* was released on January 6, 2014, announcing the opportunity to propose observations with any current *Hubble* instruments—Advanced Camera for Surveys (ACS), Cosmic Origins Spectrograph (COS), Fine Guidance Sensors (FGS), Space Telescope Imaging Spectrograph (STIS), and Wide Field Camera 3 (WFC3)—or to request funding for *Hubble* archival and theoretical research programs. The *Cycle 22 CP* carried over two initiatives from Cycle 21 relating to ultraviolet (UV) and medium-sized proposals. Recognizing the unique and limited lifetime of *Hubble* UV capabilities, the UV Initiative program encourages the community and the TAC to increase the fraction of *Hubble* time dedicated to observations at wavelengths short of 3200 Å. Additionally, ~600 orbits were nominally allocated to medium proposals, requesting 34–75 orbits, in order to boost the success rate of this historically challenging program size. For the first time, *Hubble* proposers had the opportunity to request joint observations with the National Radio Astronomical Observatory (NRAO), for up to 3% of the time on NRAO's North American facilities (Green Bank Telescope, Very Large Array, and Very Long Baseline Array). Joint *Hubble–Spitzer*, *Chandra*, *XMM–Newton*, and NOAO proposals were also possible.

Using the ASTRONOMER'S PROPOSAL TOOL, astronomers electronically submitted 1134 proposals by the *Hubble* Cycle 22 proposal deadline on April 11, 2014. Once sorted by their keywords, the proposals were assigned to individual panels. The fourteen *Hubble* Cycle 22 review panels consisted of two cosmology panels, three galaxies panels, two panels for active galactic nuclei and quasi-stellar objects, two stellar-populations panels, three star panels, and two panels for planets and solar-system objects. The designation of each science area to at least two panels minimized conflicts of interest with either reviewers or proposers. Over 140 community members, recruited from the United States, Canada, and Europe, served on the *Hubble* Cycle 22 TAC panels. Dr. Pat McCarthy of Carnegie Observatories served as the Cycle 22 TAC chair, and Prof. James Binney of University of Oxford, Dr. Catherine Cesarsky of Commissariat à l'Énergie Atomique (CEA), and Prof. Rosemary Wyse of the Johns Hopkins University served as TAC members at large.

Each panel, consisting of ~9 panelists and a panel chair, was assigned ~70–90 small (<35 orbits) and medium (35–74 orbits) proposals to review and rank. To decrease the burden on the reviewers, each reviewer submitted preliminary grades for only two-thirds of the proposals in his/her panel. About two weeks prior to the TAC meeting, those preliminary grades determined the initial ranking within each panel. Proposals in the bottom 40% of the ranking were triaged and not discussed further during the TAC process—unless resurrected by an unconflicted panelist. We assigned each proposal to a primary and secondary reviewer to lead the discussion during the three-day panel meeting. The panels regraded and ranked the non-triaged proposals. Medium proposals were ranked with small proposals. Nevertheless, each panel could vote to award panel orbits to any medium proposal (ensuring its success), or to allow the proposal to compete for orbits from the general pool allocated to the medium proposals. Additionally, all the mirror panels discussed the related large and Treasury programs, which were then ranked by the panel chairs during the merged TAC discussion. For the first time, unconflicted TAC members obtained additional reviews from external experts in order to enable a well-informed discussion for the large and Treasury programs. About a week after the TAC meeting, the Institute director performed the final review of the programs recommended by the TAC, and the Cycle 22 results were announced shortly thereafter.

The *Hubble* review process continues to strive for the highest standards of impartiality and fairness. Conflicts of interest for each reviewer are identified based on institution and publication record, and mirror panels are used to avoid strong conflicts when possible. Upon distribution of the proposals to the panel, each panelist must identify any remaining conflicts of interest, including competing proposals, mentorship relationships, and close collaborations. Panelists cannot grade proposals for which they are conflicted, and in the case of strong conflicts, cannot participate in the discussion. Additionally, the Institute has taken steps to address the unconscious gender bias of the *Hubble* TAC process that has resulted in a small but statistically significant over-representation of male PIs relative to female PIs in every *Hubble* cycle. This year, we provided only the initials for the PI and Col's given names, and removed their names from the cover page and proposal IDs. Finally, the *Hubble* TAC orientation program now includes discussion of the historical over-representation of male *Hubble* PIs and the issue of unconscious bias. These steps did not result in gender parity among the accepted Cycle 22 programs. STScI will continue to study this issue.

Results

With 263 of 1134 proposals accepted, the average *Hubble* Cycle 22 acceptance rate was 18.6%. The oversubscription rate for all General Observer programs was slightly lower this year than previous years (thanks to the completion of the *Hubble* Multi-Cycle Treasury programs), with a factor 4.25 over-subscription per program and factor 5.37 over-subscription per orbit. The over-subscription for Archival/Theory funding remains higher than earlier cycles, at factor 4.15 per proposal. Medium Proposals showed a modest improvement in their success rate, with ~13% approved (vs. ~9% approved in Cycle 21). Ultraviolet Initiative programs constituted 38% of the approved Cycle 22 Programs. European PIs lead 23% of the Cycle 22 accepted programs. One joint *HST*-NRAO program was approved, as were 2 joint *HST*-*XMM* programs, 1 joint *HST*-*Chandra* program, and three *HST*-NOAO programs. No joint *HST*-*Spitzer* programs were approved in Cycle 22.

WFC3 continues to serve at *Hubble*'s workhorse instrument, with 57% of the time allocated to the various WFC3 modes (16% WFC3/IR imaging, 8% WFC3/IR grism, 26% WFC3/UVIS imaging). ACS also remains popular despite its advanced age, with 19% of the time allocation. Finally, COS and STIS continue to offer unique windows into the ultraviolet, with 12.6% and 11.4% of the Cycle 22 time allocation, respectively.

The *Hubble* Cycle 22 time allocation was well-matched to the proposal pressure in each of the different science categories, with each category typically receiving a similar fraction of approved and requested orbits. Cosmology programs constitute the largest allocation in this cycle (22%), and the allocation of *Hubble* observations of extra-solar planets is 8.5% in this cycle. Solar system observations make up 10.9% of *Hubble* observations in Cycle 22.

Acknowledgements:

We thank all of the *HST* TAC members and external reviewers for their service on the *HST* Cycle 22 TAC. Numerous STScI personnel contributed to the support of the *HST* Cycle 22 review process. Science Policies Group astronomers Claus Leitherer, Andy Fruchter, Andrew Fox, Janice Lee, Jennifer Lotz, and Neill Reid were responsible for selecting the panelists, assigning the proposals to panels and panelists,

Summary of Cycle 22 Results

Proposals	Requested	Approved	% Accepted	ESA Accepted	ESA % Total
General Observer	884	208	23.5%	47	22.6%
Snapshot	51	7	13.7%	3	42.9%
Archival Research	113	19	16.8%	-	
AR Legacy ¹	9	3	33.3%	-	
Theory ¹	78	26	33.3%	-	
Total	1134	263	23.2%	50	23.3%
Primary Orbits	19900	3707	18.6%	540	14.6%²

¹One AR Legacy is also a Theory Proposal

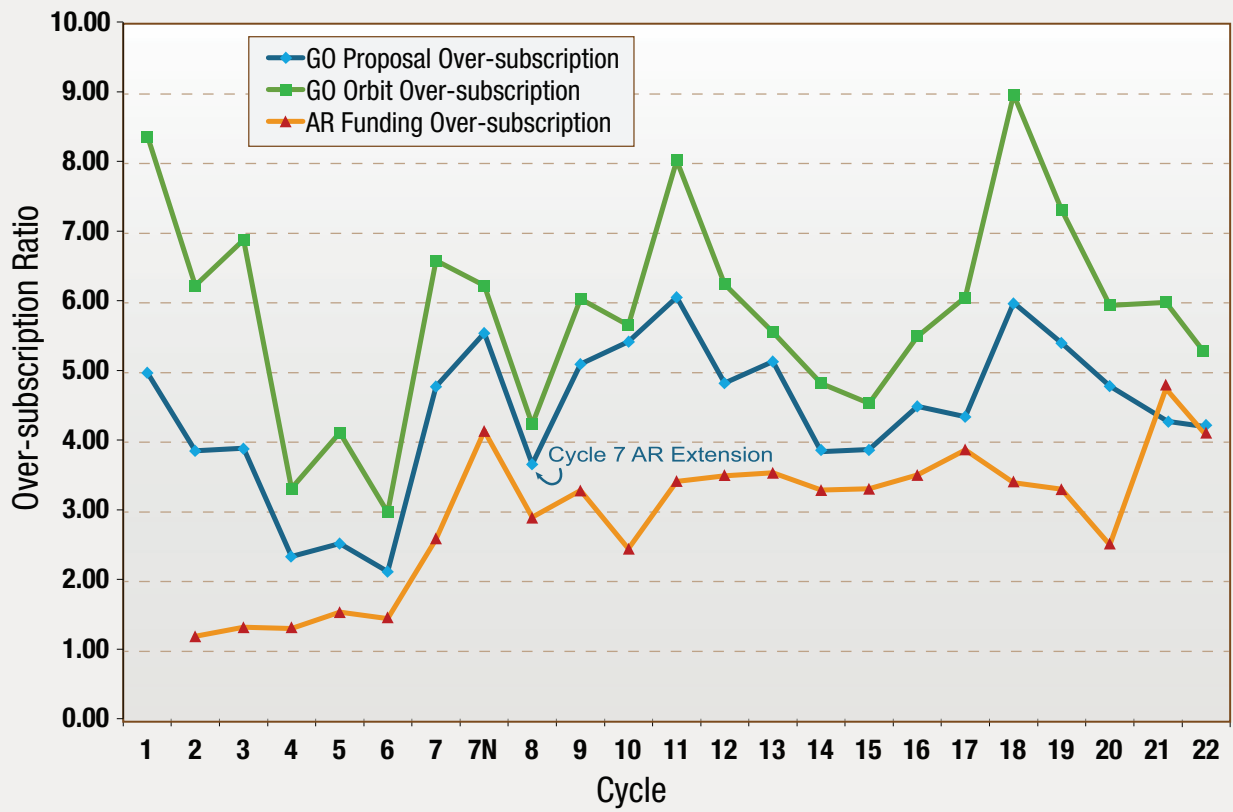
²ESA Orbit % does not include 480 Pure Parallel Orbits

coordinating policy, and providing oversight during the review. Technical Manager Brett Blacker received, organized, and distributed the proposals, oversaw the proposal database, announced the results, and prepared the statistical summaries and figures presented here. The TAC logistics were devised and coordinated by Sherita Hanna, with administrative support from Roz Baxter, Laura Bucklew, Geoff Carter, Kelly Coleman, Martha Devaud, Marvin Harris, Flory Hill, Tracy Lamb, Kari Marzola, Alisa Meizlish, Kim Oyler, Karen Petro, Karyn Poletis, Michele Sharko, Rickell Sheppard, Darlene Spencer, Rolanda Taylor, Annie Valenzuela, and Loretta Willers. Panel support was provided by Amber Armstrong, Andrea Bellini, Azalee Bostroem, Rongmon Bordoloi, Stacey Bright, Matteo Correnti, Lisa Frattare, Rebekah Hounsell, Shelley Meyett, Chris Moriarty, Molly Peebles, Karla Peterson, Tony Roman, Gregory Snyder, and Laura Watkins. Instrument expertise was provided by Marco Chiaberge, Linda Dressel, Norman Groggin, Matt Lallo, John MacKenty, Aparna Maybhate, Ed Nelan, Cristina Olivera, Charles Profitt, and Julia Roman-Duval. IT support was provided by Val Ausherman, Romeo Gourgue, Craig Hollinshead, Craig Levy, Jessica Lynch, Thomas Marufu, Greg Masci, Glenn Miller, Corey Richardson, Patrick Taylor, Calvin Tullis and other members of the Information Technology Services Division. Facilities support was provided by Andre Deshazo, Jay Diggs, Rob Franklin, Rob Levine, Glenn Martin, Greg Pabst, Sonia Saldana, Frankie Schultz, Mike Sharpe, Mike Venturella, and G. Williams. Ray Beaser, Vickie Bowersox, Margie Cook, Karen Debelius, Cathy Donellan, Adia Jones, Lisa Kleinwort, Lisa Kouroupis, Terry McCormack, Amy Power, Val Schnader, Paula Sessa, and Sarah Shin provided support from the Business Resources Center. Pam Jeffries provided support from the Office of Public Outreach, and Zak Concannon provided assistance from the Copy Center. Finally, we thank Professor Dan Reich and Bloomberg facilities staff for providing the use of meeting rooms in the Johns Hopkins Bloomberg building.

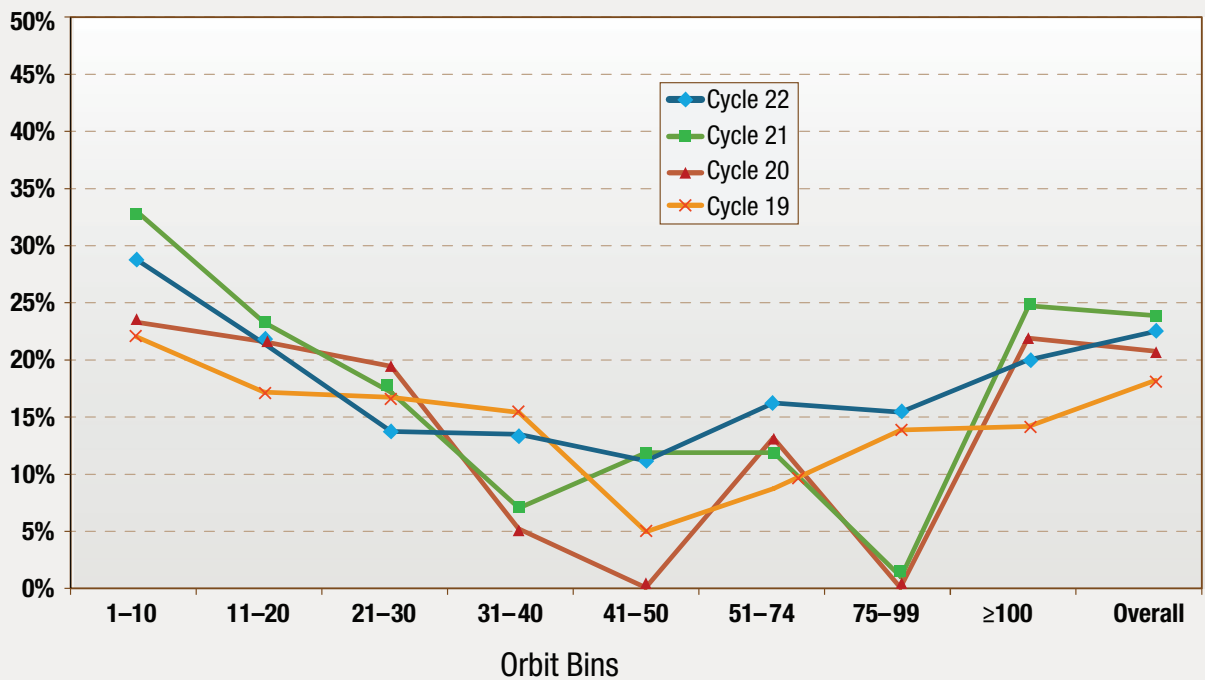
Proposal Breakdown by PI Country

Country	Submitted	Approved	Country	Submitted	Approved
Australia	12	1	Japan	9	2
Belgium	2	0	Korea	4	0
Brazil	2	1	Norway	1	0
Canada	12	4	Russia	5	0
Chile	15	2	Spain	10	1
China	7	0	Sweden	9	3
Czech Republic	1	0	Switzerland	11	3
Denmark	5	1	The Netherlands	12	4
Finland	2	0	Ukraine	1	0
France	24	6	United Kingdom	72	14
Germany	37	11	United States	842	203
Ireland	1	0	Uruguay	1	0
India	1	0			
Israel	3	2			
Italy	34	5	ESA Proposals	229	50

Proposal Acceptance Ratio: Over-subscription by Cycle



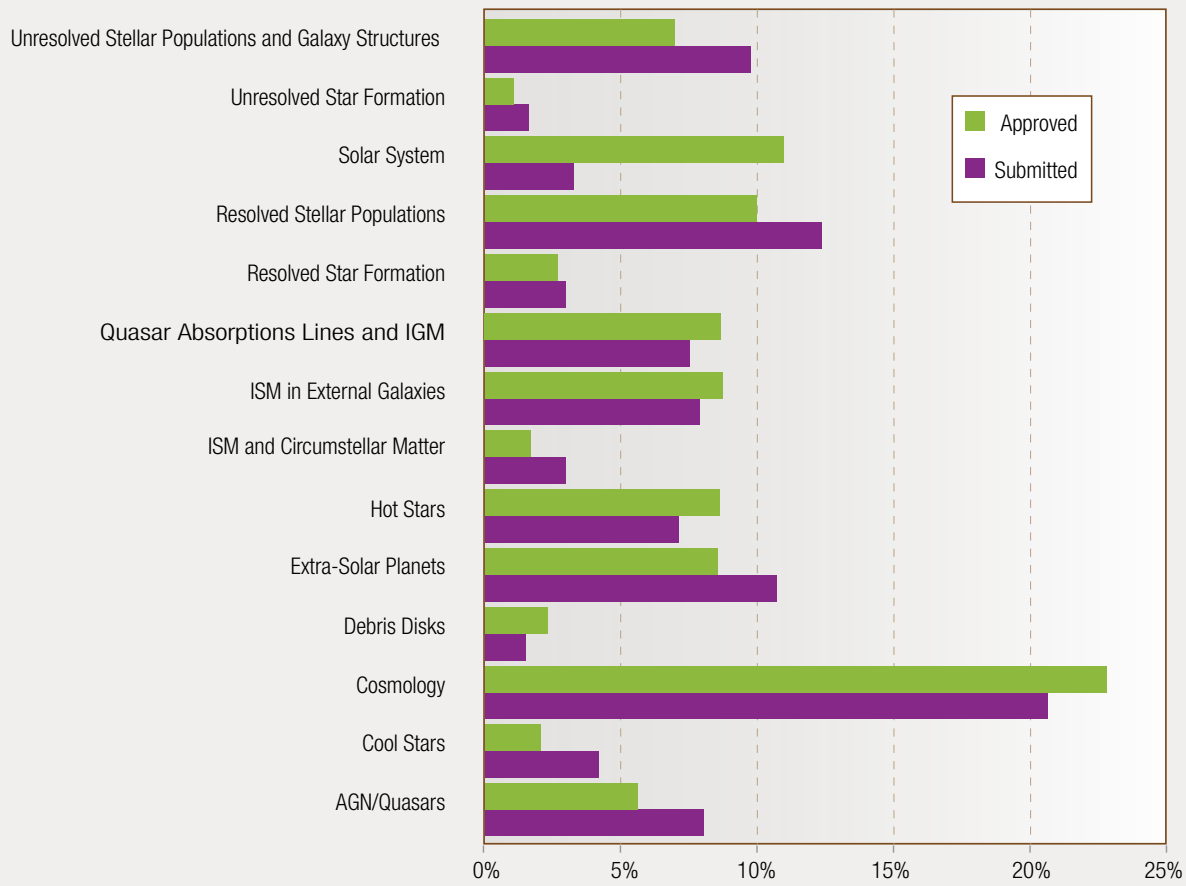
Proposal Success Rate as a Function of Orbit Request, Cycles 19–22



Cycle 22 Instrument Statistics

Configuration	Mode	Prime %	Coordinated Parallel %	Total	Instrument Prime Usage	Instrument Prime + Coordinated Parallel Usage	Pure Parallel Usage	Snap Usage
ACS/SBC	Imaging	2.1%	0.0%	1.7%			0.0%	0.0%
ACS/SBC	Spectroscopy	0.0%	0.0%	0.0%			0.0%	0.0%
ACS/WFC	Imaging	13.4%	38.4%	18.2%			0.0%	12.4%
ACS/WFC	Ramp Filter	1.3%	0.0%	1.1%	16.8%	21.0%	0.0%	0.0%
ACS/WFC	Spectroscopy	0.1%	0.0%	0.0%			0.0%	0.0%
COS/FUV	Spectroscopy	13.8%	0.0%	11.2%			0.0%	13.8%
COS/NUV	Imaging	0.1%	0.0%	0.1%	17.2%	13.8%	0.0%	0.0%
COS/NUV	Spectroscopy	3.2%	0.0%	2.6%			0.0%	0.0%
FGS	POS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
FGS	TRANS	0.0%	0.0%	0.0%			0.0%	0.0%
STIS/CCD	Imaging	1.9%	0.0%	1.5%			0.0%	0.0%
STIS/CCD	Spectroscopy	4.3%	0.0%	3.5%			0.0%	55.1%
STIS/FUV	Imaging	0.2%	0.0%	0.1%	15.5%	12.5%	0.0%	0.0%
STIS/FUV	Spectroscopy	5.3%	0.0%	4.3%			0.0%	0.0%
STIS/NUV	Imaging	0.0%	0.0%	0.0%			0.0%	0.0%
STIS/NUV	Spectroscopy	3.9%	0.0%	3.1%			0.0%	0.0%
WFC3/IR	Imaging	16.0%	21.1%	16.9%			50.0%	0.0%
WFC3/IR	Spectroscopy	8.2%	8.6%	8.3%	50.5%	52.6%	0.0%	0.0%
WFC3/UVIS	Imaging	26.2%	31.9%	27.3%			50.0%	18.7%
WFC3/UVIS	Spectroscopy	0.1%	0.0%	0.1%			0.0%	0.0%
		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Imaging	68.1	ACS	19.1%					
Spectroscopy	31.9	COS	12.6%					
		FGS	0.0%					
		STIS	11.4%					
		WFC3	56.9%					

Orbits by Science Category



*Continued
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TAC Members and Panelists

Name	Institution
TAC Members	
Patrick McCarthy, TAC Chair	Giant Magellan Telescope
James Binney, At Large	University of Oxford
Catherine Cesarsky, At Large	Commissariat a l'Energie Atomique
Rosemary Wyse, At Large	The Johns Hopkins University
Extra-Galactic Members	
Viviana Acquaviva	City University of New York
Misty Bentz	Georgia State University
Gary Bernstein	University of Pennsylvania
Gurtina Besla	Columbia University
Elizabeth Blanton	Boston University
Todd Boroson	Las Cumbres Observatory Global Telescope
Sanchayeeta Borthakur	The Johns Hopkins University
Rychard Bouwens	Universiteit Leiden
David Bowen	Princeton University
Marusa Bradac	University of California–Davis
Mark Brodwin	University of Missouri
Andrew Bunker	Oxford University
Sebastiano Cantalupo	University of California–San Diego
Michele Cappellari	University of Oxford
Caitlin Casey	University of California–Irvine
Stéphane Charlot	CNRS, Institut d'Astrophysique de Paris
Ranga Ram Chary	California Institute of Technology
Christopher Churchill	New Mexico State
Charlie Conroy	University of California–Santa Cruz
Kathy Cooksey	Massachusetts Institute of Technology
Asantha Cooray	University of California–Irvine
Alison Crocker	University of Toledo
Roelof de Jong	Astrophysikalisches Institut Potsdam
Tiziana Di Matteo	Carnegie Mellon University
Aleksandar Diamond-Stanic	University of Wisconsin–Madison
Chris Fassnacht	University of California–Davis
Natascha M. Forster Schreiber, Chair	Max-Planck-Institut für extraterrestrische Physik
Johan Fynbo	DARK Cosmology Centre
Suvi Gezari	University of Maryland
Frederick Hamann	University of Florida
Ann Hornschemeier	NASA/Goddard Space Flight Center
Tesla Jeltema	University of California–Santa Cruz
Linhua Jiang	Arizona State University

Name	Institution
Kelsey Johnson, Chair	University of Virginia
Dale Kocevski	University of Kentucky
Varsha Kulkarni	University of South Carolina
Mark Lacy	National Radio Astronomy Observatory
Tod R. Lauer	National Optical Astronomy Observatory
Nicolas Lehner	University of Notre Dame
Karen Leighly	University of Oklahoma Norman Campus
Chun Ly	NASA/Goddard Space Flight Center
Bahram Mobasher	University of California–Riverside
Leonidas Moustakas	Jet Propulsion Laboratory
Preethi Nair	University of Alabama
Benjamin Oppenheimer	University of Colorado at Boulder
Alexandra Pope, Chair	University of Massachusetts–Amherst
J. Xavier Prochaska, Chair	University of California–Santa Cruz
Sandhya Rao	University of Pittsburgh
Jane Rigby	NASA/Goddard Space Flight Center
Steven Rodney	The Johns Hopkins University
Paola Rodriguez Hidalgo	University of Toronto
Kate Rubin	Harvard-Smithsonian Center for Astrophysics
Sandra Savaglio	Max-Planck-Institut für extraterrestrische Physik
Brian Siana	University of California–Riverside
Suresh Sivanandam	University of Toronto
Dan Stark	University of Arizona
Charles Steinhardt	California Institute of Technology
Daniel Stern	Jet Propulsion Laboratory
Harry Teplitz	California Institute of Technology
David Thilker	The Johns Hopkins University
Erik Tollerud	Yale University
Kim-Vy Tran	Texas A&M University
Christy Tremonti, Chair	University of Wisconsin
Jonathan Trump	Pennsylvania State University
Sylvain Veilleux, Chair	University of Maryland
David Wake	University of Wisconsin
Bart Wakker	University of Wisconsin
Risa Wechsler	Stanford University
David Weinberg, Chair	Ohio State University
Steve Zepf	Michigan State

TAC Members and Panelists

Name	Institution
Planetary Panel Members	
David Ardila	California Institute of Technology
Gilda Ballester	University of Arizona
Travis Barman	Lowell Observatory
James Bauer	Jet Propulsion Laboratory
Jacob Bean	University of Chicago
Nuria Calvet, Chair	University of Michigan
Jay Farihi	University College of London
Yan Fernandez	University of Central Florida
Boris Gänsicke	University of Warwick
Erika Gibb	University of Missouri
Caitlin Griffith	University of Arizona
Brigette Hesman	University of Maryland
Paul Kalas	University of California–Berkeley
Nikole Lewis	Massachusetts Institute of Technology
Carl Melis	University of California–San Diego
Katie Morzinski	University of Arizona
Glenn Orton	Jet Propulsion Laboratory
Scott Sheppard	Carnegie Institution of Washington
Diana Valencia	University of Toronto
Faith Vilas, Chair	Planetary Science Institute
Galactic Panel Members	
Thomas Ayres, Chair	University of Colorado
Jeremy Bailin	University of Alabama
Martha Boyer	NASA/Goddard Space Flight Center
Elisabetta Caffau	Observatoire de Paris
Zach Cano	University of Iceland
Brian Chaboyer	Dartmouth College
Rupali Chandar	University of Toledo
Ben Davies	Liverpool John Moores University
Selma E. de Mink	Carnegie Institution of Washington
Rosanne Di Stefano	Harvard-Smithsonian Center for Astrophysics
Tuan Do	University of Toronto
Kevin France	University of Colorado
Miriam García	Centro de Astrobiología Instituto Nacional de Técnica Aeroespacial
Douglas Gies	Georgia State University
Robert Gutermuth	University of Massachusetts
Ulrike Heiter	Uppsala University
Vincent Henault-Brunet	University of Surrey

Name	Institution
D. John Hillier, Chair	University of Pittsburgh
Jon Holtzman, Chair	New Mexico State University
Christopher Johns-Krull	Rice University
Christian Johnson	Harvard University
Mansi Kasliwal	Carnegie Institution of Washington
Christian Knigge	University of Southampton
Kaitlin Kratter	University of Arizona
Andreas Küpper	Columbia University
Jessica Lu	University of Hawaii
Ann-Marie Madigan	University of California–Berkeley
Kristen McQuinn	University of Minnesota
Maryam Modjaz	New York University
Yaël Nazé	Université de Liège
David Nidever	University of Michigan
Eva Noyola	University of Texas–Austin
Jenny Patience	Arizona State University
Anne Pellerin	State University of New York–Geneseo
Giampaolo Piotto, Chair	University of Padova
Imants Platais	The Johns Hopkins University
Jose Prieto	Princeton University
Judith Provencal	University of Delaware
Ivan Ramirez	University of Texas–Austin
Marina Rejkuba	European Southern Observatory
Ian Roederer	Carnegie Institution of Washington
Roger Romani	Stanford University
Nathan Smith	University of Arizona
Donald Terndrup	Ohio State University
Eleonora Troja	NASA/Goddard Space Flight Center
Enrico Vesperini	Indiana University
Dan Weisz	University of California–Santa Cruz
Daniel Welty	University of Chicago
Klaus Werner	Eberhard Karls Universität Tübingen
Benjamin Williams	University of Washington
Jonathan Williams, Chair	University of Hawaii

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Extra-Galactic Programs				
Matthew Auger	University of Cambridge	YES	GO	A SHARP View of the Structure and Evolution of Normal and Compact Early-type Galaxies
Aaron Barth	University of California – Irvine		GO	Measuring the Black Hole Mass in the Brightest Cluster Galaxy NGC 1275
Matthew Bayliss	Harvard University		GO	Resolving Lyman-alpha Emission on Physical Scales <270 pc at $z > 4$
Alessandra Beifiori	Universitäts-Sternwarte München	YES	GO	Unveiling the Mass-to-light Distribution of High-redshift Clusters
Andrew Benson	Carnegie Institution of Washington		AR	Going out with a Bang or a Whimper? Star Formation and Quenching in the Local Group's Satellite Galaxies
Misty Bentz	Georgia State University Research Foundation		GO	High-resolution Imaging of Active Galaxies with Direct Black Hole Mass Measurements
Rongmon Bordoloi	Space Telescope Science Institute		GO	How Galaxy Mergers Affect Their Environment: Mapping the Multiphase Circumgalactic Medium of Close Kinematic Pairs
Rychard Bouwens	Universiteit Leiden	YES	GO	A Complete Census of the Bright $z \sim 9$ – 10 Galaxies in the CANDELS Data Set
David Bowen	Princeton University		GO	Baryon Structures Around Nearby Galaxies: Using an Edge-on Disk to Assess Inflow/Outflow Models
Rebecca Bowler	Royal Observatory Edinburgh	YES	GO	Unveiling the Merger Fraction, Sizes and Morphologies of the Brightest $z \sim 7$ Galaxies
Maruša Bradač	University of California – Davis		GO	The Power of the Great Observatories: Investigating Stellar Properties out to $z \sim 10$ with <i>HST</i> and <i>Spitzer</i>
Joseph Burchett	University of Massachusetts – Amherst		AR	A Deep Survey of Low-redshift Absorbers and Their Connections with Galaxies: Probing the Roles of Dwarfs, Satellites, and Large-scale Environment
Zheng Cai	University of Arizona		GO	Probing Quasar Host Galaxy of a Quasar at $z = 2.1$ with Damped Lyman-Alpha System as Coronagraph
Peter Capak	California Institute of Technology		GO	A Detailed Dynamical and Morphological Study of $5 < z < 6$ Star, Dust, and Galaxy Formation with ALMA and <i>HST</i>
Marcella Carollo	Eidgenössische Technische Hochschule	YES	GO	The Star-formation Histories within Clumpy Disks at $z \sim 2.2$
Marco Castellano	INAF, Osservatorio Astronomico di Roma	YES	GO	A Clear Patch in the Dark-age Universe? Looking for Reionization Sources around Two Bright Ly-alpha Emitting Galaxies at $z = 7$
Stephe Cenko	NASA Goddard Space Flight Center		GO	UV Spectroscopy of Newly Discovered Tidal Disruption Flares
Rupali Chandar	University of Toledo		GO	H-alpha LEGUS: Unveiling the Interplay Between Stars, Star Clusters, and Ionized Gas
Asantha Cooray	University of California – Irvine		AR	Behind the Mask: Are First-light Galaxies or Intrahalo-light Stars Dominating the Unresolved IR Background Fluctuations?
Aleksandar Diamond-Stanic	University of Wisconsin – Madison		GO	How Compact is the Stellar Mass in Eddington-limited Starbursts?
Tanio Diaz-Santos	California Institute of Technology		GO	Tracking the Obscured Star Formation Along the Complete Evolutionary Merger Sequence of LIRGs
Harald Ebeling	University of Hawaii		SNAP	Beyond MACS: A Snapshot Survey of the Most Massive Clusters of Galaxies at $z > 0.5$
Sara Ellison	University of Victoria		GO	Feeding and Feedback: The Impact of AGN on the Circumgalactic Medium

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Bruce Elmegreen	IBM T. J. Watson Research Center		GO	Multiband Observations of a Local Tadpole Galaxy
Andrew Fabian	University of Cambridge	YES	GO	H-alpha Filaments and Feedback in NGC 4696 at the Centre of the Centaurus Cluster
Xiaohui Fan	University of Arizona		GO	C _{III]} Emission in $z = 5.7$ Galaxies: A Pathfinder for Galaxy Spectroscopy in the Reionization Era
Xiaohui Fan	University of Arizona		GO	Galactic Environment of a Twenty-billion Solar-mass Black Hole at the End of Reionization
Mark Fardal	University of Massachusetts – Amherst		AR	Simulating the Impact of a Recent Merger on M31's Disk
Emanuele Farina	Max Planck Institute for Astronomy	YES	GO	The Lyman-alpha Extended Halo of a Quasar at $z > 6$
Ryan Foley	University of Illinois at Urbana – Champaign		GO	Testing the Standardizability of Type Ia Supernovae with the Cepheid Distance of a Twin Supernova
John Forbes	University of California – Santa Cruz		AR	Predictive Simulations of Metals Ejected from Galaxies in Galactic Winds
Amy Furniss	Stanford University		GO	Disentangling Signatures of Ultra-high-energy Cosmic Rays from a Unique Gamma-ray Blazar
Raphael Gobat	CEA/DSM/DAPNIA/Service d'Astrophysique	YES	GO	A Complete Census of Galaxy Activity in a Massive $z > 1.5$ cluster: Probing the SF-density Relation Down to the Low M^* Regime
Jenny Greene	Princeton University		GO	The Hosts of Megamaser Disk Galaxies (II)
Michael Gregg	University of California – Davis		GO	Morphological Transformation in the Coma Cluster
Yicheng Guo	University of California – Santa Cruz		AR	Mining the Treasuries: Dwarf Galaxies at $0.5 < z < 1$ as Lynchpins for Galaxy Formation and Feedback
Frederick Hamann	University of Florida		GO	Testing the Youth and Transition Object Status of FeLoBAL Quasars
Matthew Hayes	Stockholm University	YES	GO	Unveiling the Dark Baryons: The First Imaging of Circumgalactic OVI in Emission
Matthew Hayes	Stockholm University	YES	GO	Ultraviolet Spectroscopy of the Extended Lyman-alpha Reference Sample
Matthew Hayes	Stockholm University	YES	GO	How Lyman-alpha Bites/Beats the Dust
Timothy Heckman	The Johns Hopkins University		GO	Measuring the Impact of Starbursts on the Circum-Galactic Medium
Benne Holwerda	Sterrewacht Leiden	YES	SNAP	Starlight Absorption Reduction through a Survey of Multiple Occulting Galaxies (STARSMOG)
Cameron Hummels	University of Arizona		AR	The COS Cold Absorber Puzzle: Understanding the Metallicity and Phase of the Circumgalactic Medium
Edward Jenkins	Princeton University		GO	Using ISM Abundances in the SMC to Correct for Element Depletions by Dust in QSO Absorption-line Systems
Saurabh Jha	Rutgers the State University of New Jersey		GO	Rings within Rings: High-resolution Imaging of a Spectacular Gravitational Lens

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Jeyhan Kartaltepe	National Optical Astronomy Observatory		GO	Probing the Most Luminous Galaxies in the Universe at the Peak of Galaxy Assembly
Dale Kocevski	University of Kentucky		GO	Are Compton-thick AGN the Missing Link between Mergers and Black Hole Growth?
Michael Koss	Eidgenössische Technische Hochschule	YES	GO	A Candidate Recoiling Black Hole in a Nearby Dwarf Galaxy
Steven Kraemer	Catholic University of America		GO	Do QSOs have Narrow-line Region Outflows? Implications for Quasar-mode Feedback
Varsha Kulkarni	University of South Carolina Research Foundation		GO	Probing Structure in Cold Gas at $z \lesssim 1$ with Gravitationally Lensed Quasar Sightlines
Andy Lawrence	University of Edinburgh, Institute for Astronomy	YES	SNAP	Slow-blue PanSTARRS Transients: High-amplification Microlens Events?
Vianney Lebouteiller	CEA/DSM/DAPNIA/Service d'Astrophysique	YES	GO	Does Star Formation Proceed Differently in Metal-poor Galaxies?
Bret Lehmer	The Johns Hopkins University		GO	Unveiling the Black Hole Growth Mechanisms in the Protocluster Environment at $z \sim 3$
Claus Leitherer	Space Telescope Science Institute		AR	Unearthing a Treasure Trove of Ultraviolet Galaxy Spectra
Adam Leroy	Associated Universities, Inc.		GO	Maps of Recent Star Formation to Match ALMA Observations of the Nearest Nuclear Starburst
Andrew Levan	The University of Warwick	YES	GO	Pinpointing the Location and Host of the Candidate Tidal Disruption Swift J1112.3-8238
Jennifer Lotz	Space Telescope Science Institute		AR	Galaxy Mergers, AGN, and Quenching in $z > 1$ Proto-Clusters
Yu Lu	Stanford University		AR	Testing Feedback Models of Galaxy Formation Using COS-Halos Survey Data
Joe Lyman	The University of Warwick	YES	GO	The Environments and Progenitors of Calcium-rich Transients
Piero Madau	University of California – Santa Cruz		AR	Simulating the Circumgalactic Medium and the Cycle of Baryons in and out of Galaxies
Juan Madrid	Swinburne University of Technology		GO	Extreme Variability in the M87 Jet
Stephan McCandliss	The Johns Hopkins University		SNAP	High-efficiency SNAP Survey for Lyman-alpha Emitters at Low Redshift
Ian McGreer	University of Arizona		GO	A Powerful Starburst at $z = 5.4$ with Strong Lyman-alpha Emission: Resolved SED with <i>HST</i>
Matthew McQuinn	University of Washington		AR	Quasar Lifetimes and Helium Reionization from HeII Proximity Zones
Massimo Meneghetti	Jet Propulsion Laboratory		AR	Simulating <i>HST</i> Observations of Strong Lensing Clusters
Eileen Meyer	Space Telescope Science Institute		GO	The Real Impact of Extragalactic Jets on Their Environments: Measuring the Advance Speed of Hotspots with <i>HST</i>

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Eileen Meyer	Space Telescope Science Institute		GO	Solving the X-ray Origin Problem in Kiloparsec-scale Relativistic Jets: <i>Hubble</i> Provides the Missing Key
Adam Muzzin	Sterrewacht Leiden	YES	GO	Resolved H-alpha Maps of Star-forming Galaxies in Distant Clusters: Towards a Physical Model of Satellite Galaxy Quenching
Desika Narayanan	Haverford College		AR	Cold Galaxies on FIRE: Modeling the Most Luminous Starbursts in the Universe with Cosmological Zoom Simulations
Anna Nierenberg	University of California – Santa Barbara		GO	Detecting Dark Matter Substructure with Narrow Line Lensing
Pascal Oesch	Yale University		GO	A Spectroscopic Redshift for the Most Luminous Galaxy Candidate at $z \sim 10$
Sally Oey	University of Michigan		GO	Mapping the LyC-emitting Regions of Local Galaxies
Joshua Peek	Columbia University in the City of New York		GO	Galactic Accretion Unveiled: A Unique Opportunity with COS and M33
Molly Peeples	Space Telescope Science Institute		AR	MAST Interface to Synthetic Telescopes with yt (MISTY): Observing Simulations of the Intergalactic Medium
Steven Penton	Space Telescope Science Institute		AR	The Search for Diffuse Intergalactic and Circumgalactic Emission with the Cosmic Origins Spectrograph
Eric Perlman	Florida Institute of Technology		GO	The Physics of the Jets of Powerful Radio Galaxies and Quasars
Céline Péroux	Laboratoire d'Astrophysique de Marseille	YES	GO	The Stellar Continuum Light from Damped Lyman-alpha Absorber Galaxies Detected with Integral Field Spectroscopy
Bradley Peterson	The Ohio State University		GO	A Cepheid-based Distance to the Benchmark AGN NGC 4151
Annalisa Pillepich	Harvard University		AR	Clusters of Galaxies in the Last Five Billion Years: from the Brightest Cluster Galaxy to the Intra-cluster Light
Naveen Reddy	University of California – Riverside		GO	Stellar Populations and Ionization States of Lyman-alpha Emitters During the Epoch of Peak Star Formation
Adam Riess	The Johns Hopkins University		GO	The Fifth and Final Epoch
Andrew Robinson	Rochester Institute of Technology		AR	Do Supermassive Black Holes Really Reside at the Centers of Their Host Galaxies?
Abhijit Saha	National Optical Astronomy Observatory		GO	Establishing a Network of Next Generation SED Standards with DA White Dwarfs
Karin Sandstrom	University of Arizona		GO	A New View of Dust at Low Metallicity: The First Maps of SMC Extinction Curves
Edward Shaya	University of Maryland		GO	The Proper Motion of M31 Vast Plane Galaxy LGS3
Brian Siana	University of California – Riverside		AR	Quantifying Bursty Star Formation and Dust Extinction in Dwarf Galaxies at $0.75 < z < 1.5$
Greg Snyder	Space Telescope Science Institute		AR	Observing the Origins of Galaxy Structure in the Illustris Simulation
Daniel Stern	Jet Propulsion Laboratory		GO	Clusters Around Radio-loud AGN: Spectroscopy of Infrared-selected Galaxy Clusters at $z > 1.4$

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Thaisa Storchi-Bergmann	Universidade Federal do Rio Grande do Sul		GO	Constraining the Structure of the Narrow-line Region of nearby QS02s
David Syphers	University of Colorado at Boulder		AR	The First Direct Measurement of the 2–3 Rydberg Quasar Continuum for a Statistical Sample
Nial Tanvir	University of Leicester	YES	GO	GRB Hosts and the Search for Missing Star Formation at High Redshift
Nicolas Tejos	University of California – Santa Cruz		GO	Absorption in the Cosmic Web: Characterizing the Intergalactic Medium in Cosmological Filaments
Nicolas Tejos	University of California – Santa Cruz		AR	The Intergalactic Medium in the Cosmic Web
Nicolas Tejos	University of California – Santa Cruz		GO	Characterizing the Cool and Warm-hot Intergalactic Medium in Clusters at $z < 0.4$
Trinh Thuan	The University of Virginia		GO	Green Peas and Diagnostics for Lyman-continuum Leaking in Star-forming Dwarf Galaxies
Monica Valluri	University of Michigan		AR	Quantifying the Bias in the Masses of Supermassive Black Holes in Barred Galaxies
Pieter van Dokkum	Yale University		GO	Distances and Stellar Populations of Seven Low Surface-brightness Galaxies in the Field of M101
Pieter van Dokkum	Yale University		GO	Fluctuation Spectroscopy with the ACS Ramp Filters: a New Way to Measure the IMF in Elliptical Galaxies
David Wake	University of Wisconsin – Madison		AR	Identifying the Progenitors of Massive Early-type Galaxies: A Complete Census of the Properties of S2CLS Submillimeter Selected Galaxies
Bart Wakker	University of Wisconsin – Madison		AR	The Spectral Shape of the Ionizing Extragalactic Background Radiation at $z \sim 0$
Julie Wardlow	Dark Cosmology Centre, Niels Bohr Institute	YES	GO	The Nature and Environment of the Earliest Dusty Starburst Galaxies
Tracy Webb	McGill University		GO	Understanding the In-Situ Star Formation in a $z = 1.7$ Cluster-core Galaxy
Rogier Windhorst	Arizona State University		AR	Project ALCATRAZ: Archival Lyman-continuum and Theoretical Reionization Analysis versus z : Where, When, How and How Much Does LyC Escape?
John Wise	Georgia Institute of Technology		AR	Revealing the Properties of the Frontier Fields Galaxies
Aida Wofford	CNRS, Institut d'Astrophysique de Paris	YES	GO	COS Views of Local Galaxies Approaching Primeval Conditions
Gabor Worseck	Max-Planck-Institut für Astronomie, Heidelberg	YES	GO	A Potential Paradigm Shift in our Understanding of Helium Reionization
Guy Worthey	Washington State University		AR	Stellar Evolutionary Isochrones for Galaxy Evolution
Stephen Zepf	Michigan State University		AR	Use of Wide-Field ACS Mosaics to Determine Total Properties of Globular Cluster Systems
Planetary Programs				
Luigi Bedin	Osservatorio Astronomico di Padova	YES	GO	Astrometric Search for Planets in the Closest Brown Dwarf Binary System Luhman 16AB

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Susan Benecchi	Planetary Science Institute		GO	Precise Orbit Determination for a <i>New Horizons</i> KBO
Susan Benecchi	Planetary Science Institute		GO	Origin and Composition of the Ultra-red Kuiper Belt Objects
Marc Buie	Southwest Research Institute		GO	Observations of the Pluto System During the <i>New Horizons</i> Encounter Epoch
Elodie Choquet	Space Telescope Science Institute		GO	STIS Coronagraphy of a Debris Disk Newly Discovered Around a Young M Dwarf
John Clarke	Boston University		GO	<i>HST</i> Observations of Comet-induced Aurora on Mars during the Siding Spring Encounter
John Clarke	Boston University		GO	Seasonal Dependence of the Escape of Water from the Martian Atmosphere
Ernst de Mooij	University of Toronto		GO	Characterizing the Atmosphere of the Super-Earth 55Cnc e
Imke de Pater	University of California – Berkeley		GO	Giant Impacts on Giant Planets
John Debes	Space Telescope Science Institute		GO	An Autopsy of Dead Planetary Systems with COS
John Debes	Space Telescope Science Institute		GO	Pushing to 8 AU in the Archetypal Protoplanetary Disk of TW Hya
David Ehrenreich	Observatoire de Genève	YES	GO	Search for an Evaporating Ocean on the Super-Earth HD 97658b
Luca Fossati	Universität Bonn, Argelander Institut für Astronomie	YES	GO	Unveiling the Circumstellar Environment of the Most Extreme Hot-Jupiters
Boris Gänsicke	The University of Warwick	YES	SNAP	The Frequency and Chemical Composition of Rocky Planetary Debris around Young White Dwarfs: Plugging the Last Gaps
Carol Grady	Eureka Scientific Inc.		GO	A Chemical Inventory of Gas and Star-grazing Exocomets in HD 172555
Caitlin Griffith	University of Arizona		GO	Elementary Abundances of Planetary Systems
William Grundy	Lowell Observatory		GO	Orbits and Physical Properties of Four Binary Transneptunian Objects
Amanda Hendrix	Planetary Science Institute		GO	The Ultraviolet Spectrum of Ceres
Amanda Hendrix	Planetary Science Institute		GO	UV Spectra of the Icy Saturnian Satellites: Understanding Exogenic Processes and NH ₃ in the System
Dean Hines	Space Telescope Science Institute		GO	Imaging Polarimetry of the 67P/Churyumov-Gerasimenko with ACS: Supporting the Rosetta Mission
David Jewitt	University of California – Los Angeles		GO	<i>Hubble</i> Imaging of a Newly Discovered Active Asteroid
David Jewitt	University of California – Los Angeles		GO	Determining the Nature and Origin of Mass Loss from Active Asteroid P/2013 R3
David Jewitt	University of California – Los Angeles		GO	Determining the Nature and Origin of Mass Loss from Active Asteroid P/2013 P5
Nathan Kaib	Northwestern University/CIERA		AR	The Influence of Stellar Companions on Fomalhaut's Planetary System
Paul Kalas	University of California – Berkeley		GO	Testing the Correlation between Low-mass Planets and Debris Disks

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Paul Kalas	University of California – Berkeley		GO	Scattered-light Imaging of Fomalhaut's Ice-line Belt to Understand Dynamical Upheavals in Planetary Systems
Jian-Yang Li	Planetary Science Institute		GO	Comet Siding Spring at Mars: Using MRO to Interpret <i>HST</i> Imaging of Comets
Melissa McGrath	NASA Marshall Space Flight Center		GO	Europa's Composition as Revealed by its Atmosphere
Carl Melis	University of California – San Diego		GO	Confirming the Most Water-rich Extrasolar Rocky Body
Darin Ragozzine	Florida Institute of Technology		GO	The Intriguing Formation of Haumea's Satellites
Kurt Retherford	Southwest Research Institute		GO	Io's Atmosphere Silhouetted in Transit by Jupiter Lyman-alpha
Lorenz Roth	Southwest Research Institute		GO	Europa's Water Vapor Plumes: Systematically Constraining their Abundance and Variability
Kunio Sayanagi	Hampton University		GO	Target of Opportunity Observation of an Episodic Storm on Uranus
Eric Schindhelm	Southwest Research Institute		GO	Contemporaneous Mid-UV Spectral Coverage of Pluto and Charon Coincident with the <i>New Horizons</i> Encounter
Hilke Schlichting	Massachusetts Institute of Technology		AR	Probing Sub-km-sized Kuiper Belt Objects with Stellar Occultations
Glenn Schneider	University of Arizona		GO	Decoding Debris System Substructures: Imprints of Planets/Planetesimals and Signatures of Extrinsic Influences on Material in Ring-like Disks
Bruno Sicardy	Observatoire de Paris and Paris 6 Université	YES	GO	Observation of Chariklo's Rings and the Surroundings of Chiron
William Sparks	Space Telescope Science Institute		GO	The Ice Plumes of Europa
David Trilling	Northern Arizona University		GO	Constraining the History of the Outer Solar System: Definitive Proof with <i>HST</i>
Harold Weaver	The Johns Hopkins University Applied Physics Laboratory		GO	Using <i>Hubble</i> to Measure Volatile Abundances and the D/H Ratio in a Bright ToO Comet
Ming Zhao	The Pennsylvania State University		GO	Near-IR Spectroscopy of the Newly Discovered Benchmark Hot Jupiter WASP-103b
Galactic Programs				
Jeremy Bailin	University of Alabama		AR	A Clumpy Model for Self-Enrichment in Globular Clusters
Travis Barman	University of Arizona		AR	Modeling the Extreme Ultraviolet Radiation from M Dwarfs
Robert Benjamin	University of Wisconsin – Whitewater		GO	The Windy Milky Way Galaxy
Eric Blackman	University of Rochester		AR	Triggered Star Formation from Shock to Disk
Howard Bond	The Pennsylvania State University		GO	The Origin of Intermediate-luminosity Red Transients

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Michael Boylan-Kolchin	University of Maryland		AR	Star-formation Histories of Dwarf Galaxies: Keys to Galaxy Formation and Dark Matter Structure
Thomas Brown	Space Telescope Science Institute		GO	A Direct Distance to an Ancient Metal-poor Star Cluster
Esther Buenzli	Max-Planck-Institut für Astronomie, Heidelberg	YES	GO	A Direct Probe of Cloud Holes at the L/T Transition
Nuria Calvet	University of Michigan		AR	The Formation of Lyman-alpha Fluorescent H ₂ Lines in Protoplanetary Disks Surrounding Young Solar-mass Stars
John Cannon	Macalester College		GO	Fundamental Parameters of the SHIELD II Galaxies
Stephen Cenko	NASA Goddard Space Flight Center		GO	Characterizing New Fast Optical Transients with <i>HST</i> : Astrometry, Geometry, and Host Galaxies
Denija Crnojevic	Texas Tech University		GO	Resolving the Faint End of the Satellite Luminosity Function for the Nearest Elliptical Centaurus A
Arlin Crotts	Columbia University in the City of New York		GO	Understanding New Structures Ejected from Recurrent Nova T Pyx
Julianne Dalcanton	University of Washington		GO	Emission-line Stars in Andromeda
Annalisa De Cia	Weizmann Institute of Science		GO	The Environment of the Rarest and Most Energetic Supernovae: Do Pair-instability Explosions Exist in the Nearby Universe?
Andrea De Luca	INAF, Istituto di Astrofisica Spaziale Milano	YES	GO	Imaging the Crab Nebula when it is Flaring in Gamma-rays
Nathalie Degenaar	University of Michigan		GO	The Evolutionary Link between Low-mass X-ray Binaries and Millisecond Radio Pulsars
Jeremy Drake	Smithsonian Institution Astrophysical Observatory		GO	The First Mass and Angular Momentum Loss Measurements for a CV-like Binary
Gaspard Duchene	University of California – Berkeley		GO	Imaging the Tenuous Dusty Atmosphere of Edge-on Protoplanetary Disks
Trent Dupuy	University of Texas at Austin		GO	Dynamical Masses for Free-floating Planetary-mass Binaries
Catherine Espaillat	Boston University		GO	Testing EUV Photoevaporation Models in Young Disks
Xuan Fang	Instituto de Astrofísica de Andalucía	YES	GO	UV Mapping of the Shocks in the Extremely Collimated Outflows of the Proto-Planetary Nebula Hen 3-1475
Alex Filippenko	University of California – Berkeley		GO	Early-time UV Spectroscopy of Stripped-envelope Supernovae: A New Window
Gaston Folatelli	Institute for Physics and Mathematics of the Universe		GO	iPTF 13bvn: First Identification of the Progenitor of a Type Ib Supernova
Ryan Foley	University of Illinois at Urbana–Champaign		GO	Understanding the Progenitor Systems, Explosion Mechanisms, and Cosmological Utility of Type Ia Supernovae
Andrew Fox	Space Telescope Science Institute	YES	GO	The Smith Cloud: Galactic or Extragalactic?

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Ori Fox	University of California – Berkeley		GO	Uncovering the Putative B-Star Binary Companion of the SN 1993J Progenitor
Ori Fox	University of California – Berkeley		GO	UV Spectroscopic Signatures from Type Ia Supernovae Strongly Interacting with a Circumstellar Medium
Adam Frank	University of Rochester		AR	The Reel Deal In 3D: The Spatio-temporal Evolution of YSO Jets
Avishay Gal-Yam	Weizmann Institute of Science		GO	Explosions in Real-time: Ultra-rapid UV Flash Spectroscopy of Infant Core-collapse Supernovae
Alexandre Gellenne	Universidad de Concepción		GO	Accurate Masses and Distances of the Binary Cepheids S Mus and SU Cyg
Aaron Geller	Northwestern University		AR	Modeling the Origins of Sub-subgiant Stars
Mario Gennaro	Space Telescope Science Institute		GO	Investigating the Low-mass Slope and Possible Turnover in the LMC IMF
Or Graur	The Johns Hopkins University		GO	Constraining Type Ia Supernova Nucleosynthesis and Explosion Models Using Late-time Photometry of SN2011fe and SN2012cg
Edward Guinan	Villanova University		GO	<i>HST/COS</i> FUV Spectrophotometry of the Key Binary Solar Twins 16 Cyg A&B: Astrophysical Laboratories for the Future Sun and Older Solar Analogs
Todd Henry	Georgia State University Research Foundation		GO	Pinpointing the Characteristics of Stars and Not Stars
Benne Holwerda	Sterrewacht Leiden	YES	GO	The Anemic Stellar Halo of M101
C. Jeffery	Armagh Observatory	YES	GO	Heavy-metal, Extreme Chemistry and Puzzling Pulsation: Ultraviolet Clues to the Formation of Hot Subdwarfs
Saurabh Jha	Rutgers the State University of New Jersey		GO	The Progenitor System of a Peculiar Thermonuclear White-Dwarf Supernova
Jason Kalirai	Space Telescope Science Institute		GO	Which Stars Go BOOM?
Jason Kalirai	Space Telescope Science Institute		GO	The Metallicity Dependence of the Initial Mass Function
David Kaplan	University of Wisconsin – Milwaukee		GO	A 1.05 \odot Companion to PSR J2222-0137: the Coolest Known White Dwarf?
Mansi Kasliwal	Carnegie Institution of Washington		GO	Testing a Globular Cluster Origin for Elusive Calcium-rich Gap Transients
Wolfgang Kerzendorf	University of Toronto		GO	SN 2011fe—Tackling the Type Ia Progenitor Puzzle through Extremely Late-time Photometry
Andreas Koch	Landessternwarte Heidelberg	YES	GO	The Age-metallicity Relationship of the Galactic Bulge via Stromgren Photometry
Andrew Levan	The University of Warwick	YES	GO	The Progenitors of the Longest Duration High-energy Transients
Kevin Luhman	The Pennsylvania State University		GO	Characterizing the Sun's 4th Closest Neighbor and the Coldest Known Brown Dwarf
Nicolas Martin	Université de Strasbourg I	YES	GO	Fellowship of the Andromeda Dwarf Galaxies: A Census of their Extended Star-formation Histories

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Derck Massa	Space Science Institute		SNAP	Filling the Gap—Near-UV, Optical and Near-IR Extinction
Philip Massey	Lowell Observatory		GO	The Nature of Newly Discovered Wolf-Rayet Stars in the LMC
Philip Massey	Lowell Observatory		GO	WO-Type Wolf-Rayet Stars: the Last Hurrah of the Most Massive Stars?
Justyn Maund	The Queen's University of Belfast	YES	GO	Stellar Forensics VI: A Post-explosion View of the Progenitor of SN 2012aw
Kristen McQuinn	University of Minnesota – Twin Cities		GO	Important Nearby Galaxies without Accurate Distances
S. Megeath	University of Toledo		GO	WFC3 Spectroscopy of Faint Young Companions to Orion Young Stellar Objects
Christopher Mihos	Case Western Reserve University		GO	Stellar Populations in the Outer Disk of M101
Dan Milisavljevic	Harvard University		GO	The Double Supernova in NGC 6984
Caroline Morley	University of California – Santa Cruz		AR	A New Approach to Understanding Brown Dwarf Weather
Lida Oskinova	Universität Potsdam	YES	GO	The Donor Star Winds in High-mass X-ray Binaries
Steven Parsons	Universidad de Valparaíso		GO	Testing the Single-degenerate Channel for Supernovae Ia
Jennifer Patience	Arizona State University		GO	Brown Dwarf Atmosphere Monitoring (BAM!): Characterizing the Coolest Atmosphere
George Pavlov	The Pennsylvania State University		GO	Thermal Evolution of Old Neutron Stars
Véronique Petit	University of Delaware		GO	Probing the Extreme Wind Confinement of the Most Magnetic O Star with COS Spectroscopy
Robert Quimby	Institute for Physics and Mathematics of the Universe		GO	The First UV Spectra of a Hydrogen-rich Superluminous Supernova
Suzanna Randall	European Southern Observatory – Germany	YES	GO	Mapping the Extreme Horizontal-branch Instability Strip in omega Centauri
Seth Redfield	Wesleyan University		GO	Farewell to the <i>Voyagers</i> : Measuring the Local ISM in the Immediate Path of the Two <i>Voyager</i> Spacecraft
Nicole Reindl	IAAT, Eberhard Karls Universität Tübingen	YES	GO	Following the Rapid Evolution of the Central Star of the Stingray Nebula in Real Time
Adam Ritchey	University of Washington		GO	Constraining the Cosmic-ray Acceleration and Gamma-ray Emission Processes in IC 443
Ian Roederer	University of Michigan		AR	The <i>s</i> -process Contribution to Rare, Heavy Elements
Ian Roederer	University of Michigan		GO	A New Opportunity to Detect Iron in the Most Iron-poor Star Known
Ian Roederer	University of Michigan		AR	The Origins of Germanium and the Transition to Neutron-capture Nucleosynthesis
Philip Rosenfield	Università degli Studi di Padova	YES	GO	Constraining Models of Evolved UV-bright Stars in the M31 Bulge
Elena Sabbi	Space Telescope Science Institute		GO	A 3D View of Massive Cluster Formation in the SMC

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Hugues Sana	Space Telescope Science Institute	YES	GO	UV Spectroscopy of the Most Massive Overcontact Binary Known to Date: on the Verge of Coalescence?
David Sand	Texas Tech University		GO	A New Dwarf Galaxy Associated with an Ultra-compact High-velocity Cloud
Peter Schneider	Universität Hamburg, Hamburger Sternwarte	YES	GO	The Nature of Stationary Components in Jets from Young Stellar Objects
Benjamin Shappee	The Ohio State University		GO	Whimper of a Bang: Documenting the Final Days of the Nearby Type Ia Supernova 2011fe
Steve Shore	Università di Pisa	YES	GO	Late Nebular-stage High-resolution UV Spectroscopy of Classical Galactic Novae: a Benchmark Panchromatic Archive for Nova Evolution
Stephen Skinner	University of Colorado at Boulder		GO	Tracing Hot Plasma in the RY Tau Jet
Nathan Smith	University of Arizona		GO	Massive Stars Dying Alone: Extremely Remote Environments of SN2009ip and SN2010jp
Jennifer Sokoloski	Columbia University in the City of New York		GO	Imaging Spectroscopy of the Gamma-ray Nova V959
Mon Phillip Stancil	University of Georgia Research Foundation, Inc.		AR	An H ₂ /HD Collisional Excitation Database from High-Dimensional Quantum Dynamics Calculations: Benchmarking Interstellar STIS/COS Observations
Paula Szkody	University of Washington		GO	Unprecedented Tracking of the Unique Dwarf Nova GW Lib from Largest Amplitude Outburst to Quiescent Pulsations
Jonathan Tan	University of Florida		GO	Kinematics of a Massive Star Cluster in Formation
Nial Tanvir	University of Leicester	YES	GO	<i>r</i> -process Kilonova Emission Accompanying Short-duration GRBs
Maureen Teyssier	Rutgers the State University of New Jersey		AR	Interpreting Resolved Stellar Populations in Local Group Dwarfs: Results from Cosmological Simulations
David Thilker	The Johns Hopkins University		GO	The Controversial Nature of the Diffuse UV Emission in Galaxies: Exploring NGC 300
Erik Tollerud	Yale University		GO	Resolving the Tip of the Red Giant Branch of Two New Candidate Local Group Dwarf Galaxies
Roeland van der Marel	Space Telescope Science Institute		GO	The Proper Motion Field along the Magellanic Bridge: a New Probe of the LMC-SMC Interaction
Schuyler Van Dyk	California Institute of Technology		GO	A Wolf-Rayet Progenitor for iPTF13bvn?
Schuyler Van Dyk	California Institute of Technology		GO	The Stellar Origins of Supernovae
Nolan Walborn	Space Telescope Science Institute		AR	Comparative Precise Parameters for OB Stars in Three Galaxies
Matthew Walker	Carnegie Mellon University		GO	Is the Crater Satellite the Milky Way's Smallest Dwarf Galaxy or its Largest Globular Cluster?
Lifan Wang	Texas A & M University		GO	Polarimetry of SN 2014J in M82 as a Probe of Its Dusty Environment
Daniel Weisz	University of California – Santa Cruz		GO	Completing the Census of Isolated Dwarf Galaxy Star-formation Histories
Klaus Werner	Eberhard Karls Universität Tübingen	YES	GO	Trans-iron Group Elements in Hot Helium-rich White Dwarfs

Accepted Proposals

Name	Institution	ESA Member	Type	Title
Benjamin Williams	University of Washington		AR	The Masses of M31 Supernova Remnant Progenitors
David Wilson	The University of Warwick	YES	GO	Accretion of Planetary Debris onto the Unique White Dwarf GD394
Stephen Zepf	Michigan State University		GO	Testing Models of the Black Hole X-ray Source in the NGC 4472 Globular Cluster RZ2109 with COS UV Spectroscopy
Large Programs				
Björn Benneke	California Institute of Technology		GO	Exploring the Diversity of Exoplanet Atmospheres in the Super-Earth Regime
Wendy Freedman	Carnegie Institution of Washington		GO	CHP-II: The Carnegie <i>Hubble</i> Program to Measure H0 to 3% Using Population II
Michael Gregg	University of California – Davis		SNAP	Completing the Next Generation Spectral Library
Saul Perlmutter	University of California – Berkeley		GO	See Change: Testing Time-varying Dark Energy with $z > 1$ Supernovae and their Massive Cluster Hosts
Evan Skillman	University of Minnesota – Twin Cities		GO	Is the First Epoch of Star Formation in Satellite Galaxies Universal? - Part II
John Spencer	Southwest Research Institute		GO	A Kuiper Belt Object for the <i>New Horizons</i> Mission
Todd Tripp	University of Massachusetts – Amherst		GO	The COS Absorption Survey of Baryon Harbors (CASBaH): Probing the Circumgalactic Media of Galaxies from $z = 0$ to $z = 1.5$
Treasury Programs				
Kevin France	University of Colorado at Boulder		GO	The MUSCLES Treasury Survey: Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems
Sangeeta Malhotra	Arizona State University		GO	The Faint Infrared Grism Survey (FIGS)
Pascal Oesch	Yale University		GO	The GOODS UV Legacy Fields: A Full Census of Faint Star-forming Galaxies at $z \sim 0.5-2$
Massimo Robberto	Space Telescope Science Institute		GO	The Orion Nebula Cluster as a Paradigm of Star Formation
Pure Parallel Program				
Michele Trenti	University of Cambridge	YES	GO	Bright Galaxies at <i>Hubble's</i> Detection Frontier: The Redshift $z \sim 9-10$ BoRG Pure-parallel Survey
AR Legacy Programs				
Justin Ely	Space Telescope Science Institute		AR	The Lightcurve Legacy of COS and STIS*
Gary Ferland	University of Kentucky		AR	What AGN Reverberation Maps Tell Us: Plasma Simulations of Dense Accreting Gas
Morgan Fouesneau	University of Washington		AR	A Legacy Magellanic Clouds Star Clusters Sample for the Calibration of Stellar Evolution Models
Mariska Kriek	University of California – Berkeley		AR	Maximizing the Impact of CANDELS: Rest-frame Optical Spectroscopy of 2000 Galaxies at $1.4 < z < 3.8$

*Program not included in the statistics of this article

ACS and WFC3 Calibration Improvements: Lessons from *Hubble* Frontier Fields

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Introduction

Hubble Frontier Fields (HFF) is an ongoing *Hubble Space Telescope* cross-instrument multi-cycle Director's Discretionary time program (PI J. Lotz/M. Mountain)¹ that will observe six lensing clusters of galaxies with both the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). In the past, many large *Hubble* proposals have been drivers of calibration improvements, and this side benefit is an important part of executing HFF, too. A priority of HFF is to make the new methods available to the astronomy community. The purpose of this article is to describe several calibration improvements due to HFF.

SELCAL

The SELFCAL algorithm, written by Jay Anderson, can detect small-scale artifacts that are not corrected by the ACS default pipeline and reference files. SELFCAL uses multiple dithered images of the same field, and tracks the pixel values that move with the dither from those that don't. The consistently

moving pixel values, called the "science" image, are tagged as real astronomical sources and sky background. Other artifacts, like hot pixels and amplification offsets, which are present in a majority of the image set but do not move with the dither, are compiled into a final image called the "delta dark." The delta dark is then subtracted from each of the original science images. For HFF, we see a 20% increase in signal-to-noise ratio (S/N) after SELFCAL processing [Anderson, in prep]. Figure 1 shows a HFF image with and without the SELFCAL correction. In the final HFF mosaics we see a 0.5 magnitude improvement in the depth of the cluster field after SELFCAL has been applied. The SELFCAL software is available for public use, although unsupported by the Institute. More details can be found online.²

ACS de-stripping

Following Servicing Mission 4 and the replacement of the CCD electronics box, ACS has suffered from row-correlated noise, called "stripping." Nevertheless, this noise is consistent enough that it can be modeled and removed. There are currently two solutions in place to subtract the noise from images. The first solution is part of CALACS, which calculates the correction using the physical prescan area (columns of pixels at the sides of each chip that are not exposed to light). Unfortunately there are not many prescan pixels to work with, so this correction is not reliable for some near-edge cases. The second solution—packaged as a stand-alone PYTHON code—uses the actual image pixels to calculate the stripe noise.

A vulnerability of this second approach is that bright objects in the image can throw off the stripe calculation. To solve this, the ACS team has included an option in the stand-alone de-stripe code to provide an object mask. The masked pixels will not be used for the stripe calculation. A new PYTHON script released by the ACS team, called ACS_DESTRIPE_PLUS, has combined these changes with the ACS charge transfer efficiency (CTE) correction and the regular components of the CALACS pipeline,³ allowing users to easily take advantage of these improvements to the standard pipeline. Figure 2 shows the two versions of an ACS image, one processed with ACS_DESTRIPE_PLUS and one processed with default CALACS.

WFC3 IR time-variable background

Recent analyses have discovered that emission from helium in the atmosphere above *Hubble* causes an excess background signal in some Wide Field Camera 3/Infrared (WFC3/IR) data (Mackenty &

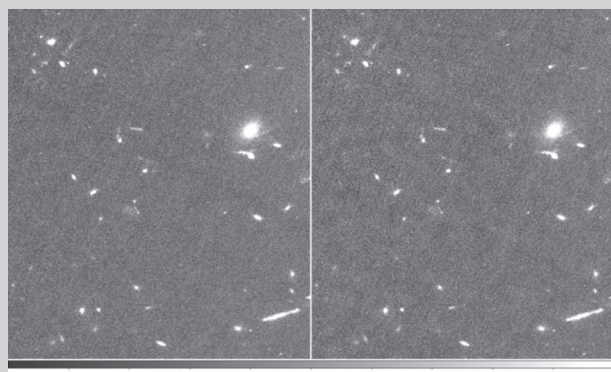


Figure 1: Final drizzle combined Frontier Fields image of cluster Macs 0416 in ACS/F435W. *Left:* The image has been processed with SELFCAL. *Right:* The image with standard CALACS processing.

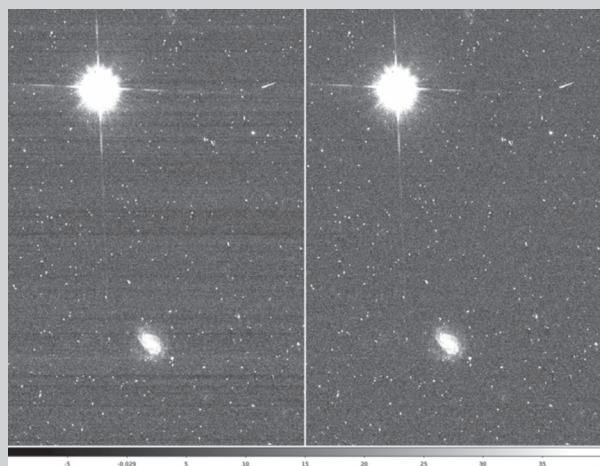


Figure 2: *Left:* A 2013 ACS sub-array image processed with the default CALACS pipeline. *Right:* The same image, processed with the ACS_DESTRIPE_PLUS script, which combines CTE correction and the stand-alone de-stripe code with object masking.

Brammer 2014; Brammer et al. 2014). This excess signal, dubbed “time-variable background” (TVB), varies with the orbital geometry of *Hubble*. For long IR exposures, this varying background can cause a noticeable non-linearity in the resulting data (see Figure 3).

To remove the effects of TVB, an algorithm was created that works on raw WFC3/IR images (Robberto, M. 2014).⁴ It calculates the amount of TVB signal from each readout, and subtracts it from the data. The corrected raw data can then be run through the CALWFC3 pipeline to produce an uncontaminated signal-rate image. To find the amount of TVB signal in the reads of a given pixel, we model the expected signal of an uncontaminated pixel and compare this with the measured signal. Since the correction is performed on raw data, our model consists of a signal that is a linear function of time, multiplied by a function that represents the non-linearity inherent to the IR detector. This idealized model is fitted iteratively to the data. Reads with a large residual compared to the model are assumed to contain TVB signal and are thrown out, and the fit is repeated.

Refining the ACS/WFC Distortion Solution

The ACS instrument team has been working to develop more accurate geometric distortion solutions. The old solution lacked an accurate way to describe the pixel grid distortion and the non-polynomial components. There were also inaccuracies with the time-dependent component. These problems meant that the alignment derived for images taken with a long time baseline, or with large offsets, were not optimal. Additionally, the alignment of ACS images with other *Hubble* instruments was not optimal. Included in the changes made to the solution are an added polynomial term for distortion solution and calibrations for the linearly evolving terms of the time dependency.

The HFF program has strict requirements on the alignment precision. Alignment needs to be done across filters and instruments. Additionally, some of the targets in the HFF program have extant data taken with large offsets and with long time baselines. Thus, the HFF data provides an exquisite testbed for updated distortion solutions. The ACS team used these data to vet the updated distortion solution and ensure it met the strict alignment requirements of the HFF project. The updated solutions are now capable of obtaining astrometric alignment residuals below 0.05 ACS/WFC pixels (2.5 milliarcseconds; Borncamp et al. 2015).

Conclusion

With ambitious projects such as HFF, *Hubble* continues to reach deeper into the sky and produce a wealth of new science discoveries. With this increased depth, precision calibration becomes increasingly important and an absolute necessity for successful science. The *Hubble* instrument teams will continue to collaborate with science-driven initiatives, stimulating improved calibrations in the future.

Acknowledgments

Contributions to this work were made by the HFF pipeline team (A. Koekemoer, J. Mack, S. Ogaz, B. Hilbert, R. Avila, J. Anderson, M. Robberto, D. Borncamp, H. Khandrika, B. Porterfield, R. Lucas, E. Barker, D. Hammer, A. Fruchter, and J. Lotz), the ACS team (in particular V. Platais, S. Ogaz, N. Grogan), and the WFC3 team (in particular G. Brammer, J. MacKenty, B. Hilbert).

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¹ <http://www.stsci.edu/hst/campaigns/frontier-fields/>

² <http://www.stsci.edu/hst/acs>

³ <http://www.stsci.edu/hst/acs/software/destripe/>

⁴ <http://archive.stsci.edu/pub/hlsp/frontier/scripts/time-variable-sky/>

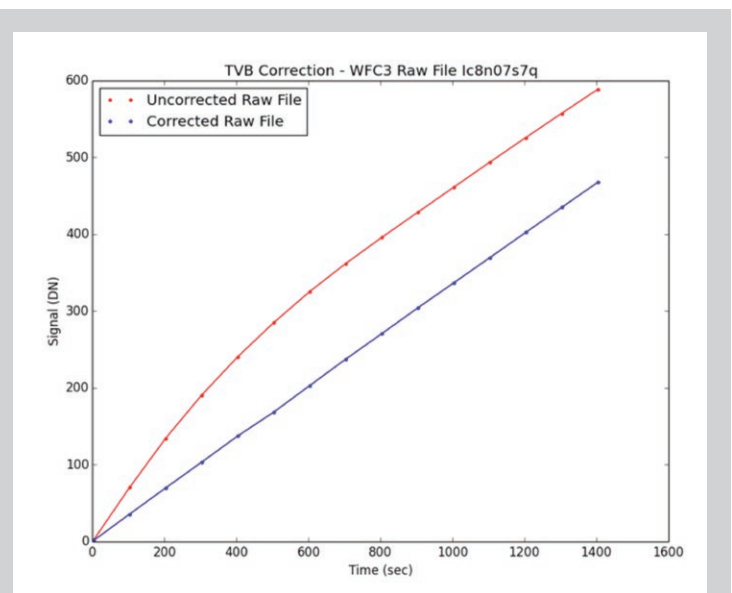


Figure 3: The red curve shows the original reads from image ic8n07s7q, while the blue curve shows ic8n07s7q after performing the TVB correction, returning the background to a linear function. Data courtesy of Harish Khandrika.

Exquisite Astrometric Measurements with WFC3 to Refine *Hubble's* Measurement of the Hubble Constant

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One of the original scientific objectives for the construction of the *Space Telescope* was the accurate measurement of the expansion rate of the universe. This seminal discovery of 20th century astronomy by Edwin Hubble fundamentally changed our understanding of the history of the universe—arguably the founding discovery of modern observational cosmology. The determination of the expansion rate, now known as the Hubble Constant, relies upon measuring the recession velocity of distant galaxies (a relatively easy measurement) and also measuring their distances (a famously difficult measurement). Today, *Hubble Space Telescope*, almost 25 years after its launch, is still making breakthrough contributions.

The primary method of measuring the distances of remote galaxies depends upon measuring the *apparent* brightness of a source of known *absolute* brightness. Ultimately, this task comes down to determining the absolute brightness of a particular type of astronomical object. The most popular local class of objects is the Cepheid variable stars (also used by Hubble as the foundation of his original discovery of the universe's expansion). These very bright stars have a strong correlation between the period of their variation and their absolute brightness. Cepheids are sufficiently bright that modern telescopes—especially *Hubble*—can precisely measure their brightnesses in fairly distant galaxies,

where overlap with even brighter sources (e.g., supernovae) can extend distance measurements to much larger distances. Extensive efforts by multiple teams over the past quarter century, using successive *Hubble* cameras, have reduced the uncertainty in the known value of the Hubble Constant from a factor of two down to a little over 3% (see Freedman 2001; Sandage 2006; Riess 2006, 2011; Freedman 2012; Sorce 2012; Suyu 2012, and references therein). It is worth noting that the pre-launch science goal for *Hubble* was to determine the Hubble Constant to 10%!

The availability of the Wide Field Camera 3 (WFC3) after Servicing Mission 4 in 2009 opened two new avenues to improve our measurement of the Hubble Constant. First, WFC3's infrared channel obtains highly sensitive measurements at wavelengths of light less impacted by dust within galaxies. This reduces the uncertainties in our measurements of the brightness of both Cepheid variable stars and supernovae to the point where the calibration of Cepheid variables in our galaxy has become the dominant factor in a precise determination of the Hubble Constant.

The second avenue to improving the Hubble Constant was not anticipated during the design and development of WFC3, but arose from the Institute's efforts to support precision spectrophotometric measurements of exoplanet transits—a topic very far removed from fundamental cosmological observations! This was the development of the “spatial scan” capability for WFC3. In this mode, the telescope is intentionally moved at a precisely controlled rate

during the science observation. Thus, instead of stars presenting a nice round, star-like image, they appear as streaks (see Figure 1). For an observer seeking to acquire the maximum number of photons while an exoplanet is eclipsed by its star, the spatial-scan mode dramatically improves the quality and efficiency of the observations.

The relevance of the spatial-scan technique to Cepheid variable stars rests on establishing the essential relationship between their period and absolute luminosity. As before, measuring the period is easy, but the absolute luminosity requires knowing their distances. These may be determined via parallax

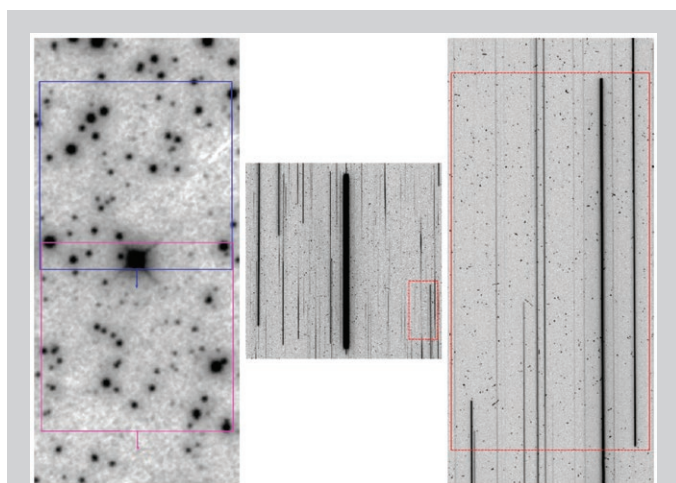


Figure 1: (Left) Cepheid SY Aur as seen in the Digital Sky Survey. The WFC3/UVIS field of view during the spatial scan moves from the magenta to the blue box. (Center) F606W spatial scan image from DD program 12879. The bright vertical trace in the center is the Cepheid star. (Right) A zoomed view of the region in the red box showing the numbers (and increasing faintness) of field stars.

measurements using the motion of the earth around the sun. Since the earth–sun distance is well known, the problem is reduced to simple trigonometry with a *very* long skinny triangle.

Prior to WFC3, the finest *Hubble* angle measurements were obtained using the telescope’s Fine Guidance Sensors (FGS). These were able to measure the distances to Cepheid variable stars out to ~500 parsecs, or ~1600 light-years. A measurement of parallax of one arc second equals one parsec of distance—hence the astronomical use of this distance unit. Thus, 1000 parsecs requires measuring the relative position of the Cepheid variable star to 0.001 arc seconds (for a signal-to-noise of one) compared to distant background stars at two instances separated by half a year. Careful measurements of the available Cepheid variables within ~500 parsecs of the sun were obtained using the FGS (Benedict 2007). Unfortunately, this volume contains only a rather limited number of these rare stars, including only one of the brightest Cepheids—those most easily observed in the more distant galaxies, with periods greater than 10 days.

Today, improving the calibration of the Cepheid period–luminosity relationship is the key to improving the measurement of the Hubble Constant. If the distances to more distant Cepheid variable stars could be directly determined via the parallax method, the population of such stars would increase as the cube of the increased distance (or square in the case of a disk population). The improved calibration would increase the statistical value of the measurements (more stars) and include far more of the brightest Cepheid variables (reduced systematic uncertainties).

Enter the WFC3 spatial-scan mode. In a typical image obtained by the carefully calibrated WFC3 ultraviolet-visible channel (UVIS), the position of a bright star can be measured to 1% of a pixel (0.040 arc seconds per pixel). Combined with the residual uncertainties in the calibration of the relative positions of the pixels, the UVIS channel provides a measurement of about 2% of a pixel—slightly inferior to FGS measurements. Nevertheless, if the WFC3 measurements were to be repeated a large number of times, these uncertainties could be significantly reduced. Of course, taking hundreds or thousands of images of each Cepheid would use an impractically large amount of *Hubble* observing time. Therefore, our solution exploits the WFC3 spatial-scan mode.

By moving the image of a Cepheid variable star (and the other stars in the field) across several thousand pixels during an exposure, the individual positions of the stars along the axis perpendicular to the scan direction are measured ~1000 times. If the uncertainties were purely random errors, we would achieve a factor of ~30 improvement in the precision of parallax measurements, which would increase the accessible volume for the measurement of Cepheid variable stars by a factor >1000 compared to the FGS studies.

As we enter this domain of very high astrometric precision, rather than use arc seconds as the unit of measurement, it is helpful to use micro-arc seconds (μ as)—millionths of an arc second. The FGS is capable of measuring star separations to an accuracy of ~400 μ as and the WFC3/UVIS accuracy of ~800 μ as in imaging mode. With spatial scans we could expect to achieve relative measurements around 30 μ as perpendicular to the scan axis. This would enable the direct measurement of the distances to Cepheid variable stars out to ~5000 pc and dramatically increase the available sample.

Of course, nothing is that easy. To accomplish these measurements requires careful correction for both astronomical

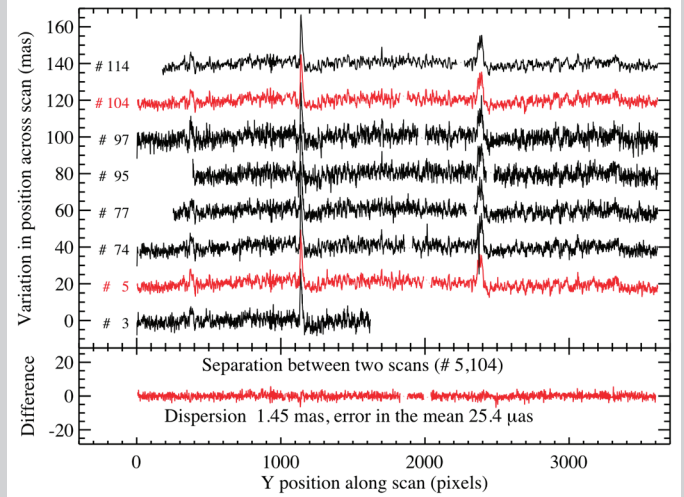


Figure 2: Relative positions of stars from the image in Figure 1. The telescope jitter is clearly visible as strongly correlated noise. Each trace has been offset to align the jitter. Comparing the positions of two stars in this field (indicated in red) reduces the dispersion from ~10 to 1.45 milli-arc seconds. Averaging along the scan yields a mean error of 25.4 micro-arc seconds.

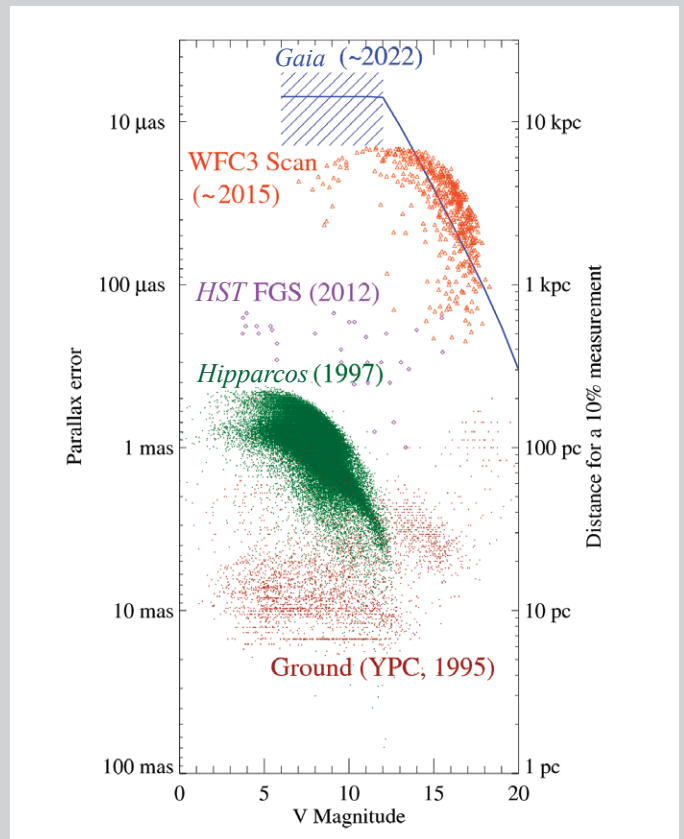


Figure 3: Relative precision in micro-arc seconds as a function of magnitude. The figure shows actual or expected parallax measurements from the ground-based Yale Parallax Catalog (YPC), *Hipparcos*, FGS, WFC3, and *Gaia*. YPC and *Hipparcos* measurements are only included if better than 3 sigma. The WFC3 points show the estimated end-of-program uncertainties for all stars in our Cepheid fields, including reference stars. It is interesting to note that at fainter magnitudes, *Hubble* is potentially more capable than *Gaia*.

and instrument factors. The primary astronomical issue is that Cepheids are very bright stars. While this brightness enables their observation in more distant galaxies, it also means that many of the stars within the field of view around the Cepheid are actually relatively nearby and thus not suitable as background stars for parallax measurements. In practice, we must obtain photometric data for the stars in these fields, in addition to the astrometric data, in order to identify the background luminous K giant stars and to acquire photometric parallax measurements of the neighboring stars. The observations also must be designed to accommodate the very large dynamic range between the Cepheid stars and the fainter background stars. These needs can be accommodated by a combination of varying scan speeds and using broad- and narrow-bandpass filters. The instrumental calibrations included: (1) careful extraction of the star trails and aligning their positions to remove the effects of spacecraft jitter; (2) a more precise calibration of the geometric distortions within the WFC3/UVIS channel, using the spatial scans of the open cluster M35; (3) corrections for velocity aberration; and (4) limitations in the control of *Hubble*'s roll angle during the spatial scan exposures. These calibrations are discussed in some detail in Riess et al. (2014).

Spatial scan observations enable a broader effort to measure parallaxes (and simultaneously WFC3/IR photometry) for the 19 Cepheid variable stars reachable with WFC3. These measurements have the potential to reduce the uncertainty in our knowledge of the Hubble Constant to less than 2% and provide a key step to the ambitious goal of reaching 1%.

Hubble proposals 12679, 12879, 13334, 13678, and 13686 over Cycles 18, 20, 21, and 22 are obtaining the Cepheid observations. As distance measurements from the European Space Agency's *GAIA* mission become available, the set of Cepheid distance measurements will increase. *Hubble* infrared photometry for some of these additional stars is being obtained via general-observer proposals 13335 and 13928.

The story will not end here. The measurements of the Hubble Constant are critical to modern cosmology, and may become important to fundamental physics, if constraints on the number of neutrino species are confirmed. Also, numerous cross checks using alternative methods will be required, as well as the refinement of measurements out to larger scales, because the Cepheid variable stars only establish the first major rung of the distance ladder. Ongoing measurements of supernovae and other methods will continue to advance.

The development of spatial scanning to enable micro-arc second measurements opens other scientific possibilities, and illustrates the continuing enhancement of *Hubble*'s capabilities, even 25 years into the mission.

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Version 1 of the *Hubble* Source Catalog

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Hubble has been in orbit for nearly 25 years, and has compiled an impressive legacy of observations. The statistics alone make the point with a dozen different instruments, roughly a hundred observing modes, several hundred different filters and gratings, tens of thousands of targets, and over a million observations. While this great volume and diversity is one of the great strengths of *Hubble*, it also makes it difficult to effectively use the archives in some cases, which is the motivation for the *Hubble* Source Catalog (HSC; <http://archive.stsci.edu/hst/hsc/>).

For example, imagine that you are interested in obtaining a color–magnitude diagram for all *Hubble* observations of the Small Magellanic Cloud (SMC). A search of the *Hubble* Legacy Archive (HLA; hla.stsci.edu) would show 7289 observations in this region (see Figure 1)!

After retrieving the data you would need to: (1) combine the various images; (2) perform photometry on roughly 10 million separate detections of 1 million individual objects; and (3) figure out how to match all those objects, in order to sort out duplicates and sum the data for repeat visits with the same instrumental configuration. Imagine the amount of time and effort this would take. With the HSC, you can now perform this task in minutes!

In many ways, the HSC provides entry into the world of database astronomy, by collecting useful information into a database that can be easily searched. The Sloan Digital Sky Survey (SDSS; see upper right panel in Figure 2) is leading the way in this rapidly growing field of astronomy. Taking a page from the SDSS book, the goal of the HSC is to combine the data from all the sources observed by *Hubble* over the years into a single master catalog.

HSC is still in its infancy, including at present only observations from Wide Field Planetary Camera 2 (WFPC2), the Wide Field Camera of the Advanced Camera for Surveys (ACS/WFC), and Wide Field Camera 3 (WFC3). Other instruments will be added in the future, including the ACS High Resolution Camera (ACS/HRC) and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS).

Version 1 of the HSC, released in February 2015, is already a very powerful new tool. The purpose of this article is to introduce HSC to the community and demonstrate how it can be used for research. In particular, we highlight the expanded opportunity for archival research proposals in Cycle 23.

As demonstrated in Figure 2, the great depth and increased spatial resolution of the *Hubble* images provide a dramatic increase in the number of sources in a given region as compared with SDSS.

Detailed examples are provided to guide potential users in common ways to use the HSC and avoid common pitfalls (http://archive.stsci.edu/hst/hsc/help/HSC_faq.html#use_case). Results from one case study are shown in Figure 3. It shows how variable stars can be found by searching for stars with large photometric scatter in repeat observations, in this case for the dwarf galaxy IC 1613. This figure also

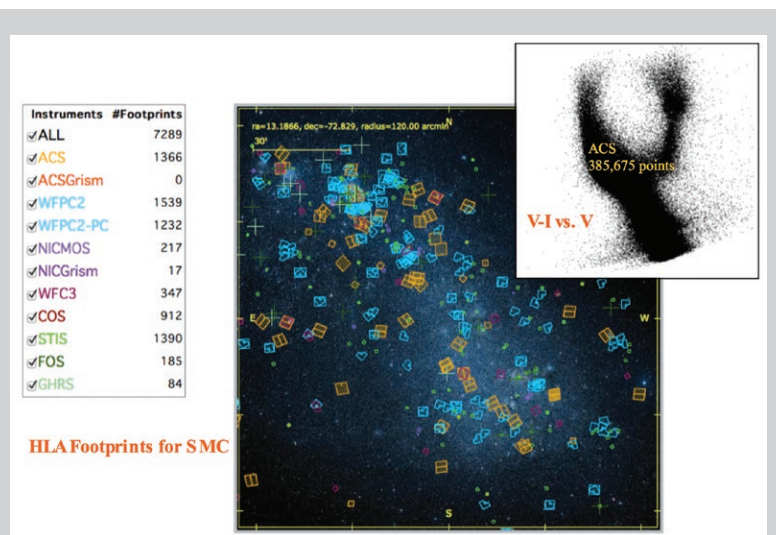


Figure 1: HLA footprints for a search of the SMC using a radius of 2 degrees. A color-magnitude diagram containing 385,675 data points, created by the HSC in less than 2 minutes, is shown in the upper right.

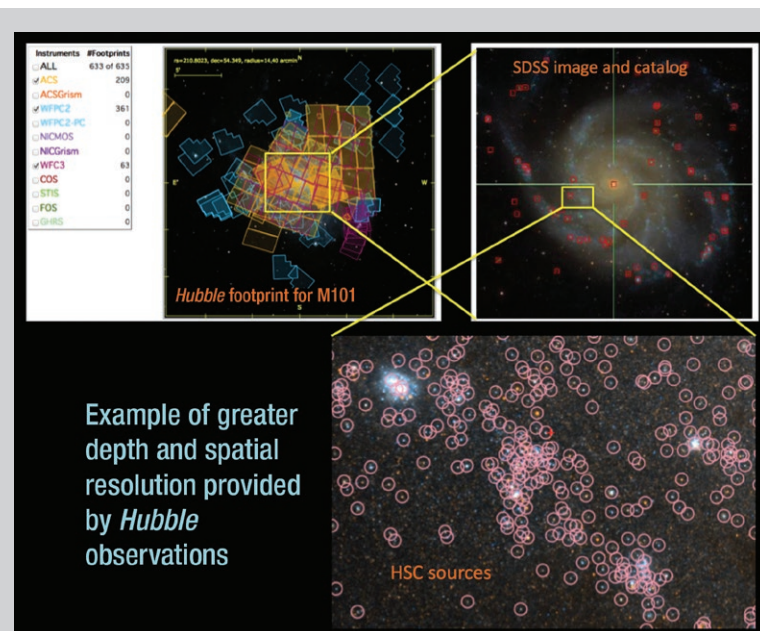


Figure 2: HLA footprint, SDSS image and catalog, and HSC sources for a portion of M101. The pink circles show the HSC detections.

Time-variable phenomena—The HSC supports time-variable studies over >20 year baseline.

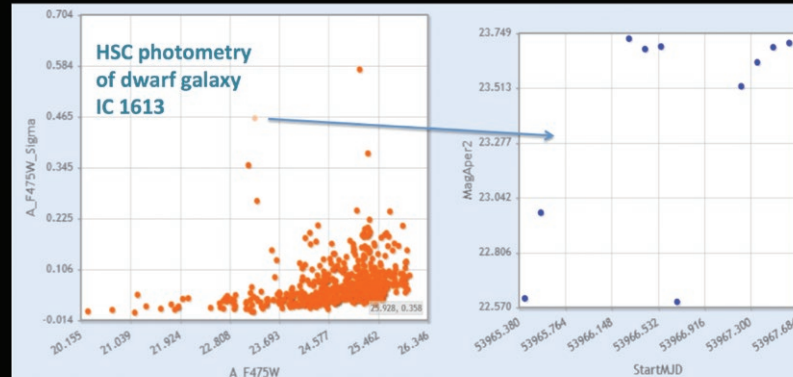


Figure 3: Example of results from a use case demonstrating how the photometric scatter in repeat ACS observations using the F475M filter can be used to find variable stars in the dwarf galaxy IC 1613. The light curve on the right shows that the star with a large value of sigma is indeed a variable.

demonstrates that the photometry in the HSC is typically accurate to a few hundreds of a magnitude based on repeat observations of non-variable stars.

While variability is a good example of how the HSC might be used (and in fact has already sparked an ESA-funded project to build a *Hubble* Catalog of Variables), several other potential examples are also listed in section 7.4 of the *Hubble Space Telescope* Primer for Cycle 23 <http://www.stsci.edu/hst/proposing/documents/primer/primer.pdf>.

Examples include: (1) extractions from extremely large data sets (e.g., Figure 1); (2) cross-matching with other catalogs (e.g., SDSS, Two Micron All Sky Survey, spectral catalogs, personal catalogs, etc.); (3) identification and determination of object properties (e.g., star clusters and associations, colors, elongations); (4) measurements of astrometric properties (e.g., proper motions, cluster kinematics, identification of Kuiper Belt objects); and (5) measurement of photometric redshifts.

Now, with the reader's interest hopefully piqued, here are some technical details.

- The HSC is derived from visit-based source lists from the HLA, built using the SOURCE EXTRACTOR software (Bertin & Arnouts 1996).
- The matching algorithms used by the HSC are described in Budavari & Lubow (2012).
- The HSC can be accessed in three ways. (1) For most cases, the Discovery Portal of the Mikulski Archive for Space Telescopes is the best choice <http://mast.stsci.edu/>, (2) For large queries, a CASJobs (CAS: Catalog Archive Server) capability is available, similar to the one developed for SDSS. (3) For certain detailed queries, the HSC homepage (<http://archive.stsci.edu/hst/hsc/>) is appropriate.
- A draft journal-level publication describing the HSC, the quality of the data, and the potential for doing science with the catalog is available. This can be found, along with other useful information, in a FAQ—available at http://archive.stsci.edu/hst/hsc/help/HSC_faq.html.
- Figure 4 shows the current photometric accuracy available for the different instruments. Note that ACS artificially appears to be much better than WFC3, primarily because these HLA source lists do not currently attempt to go as deep as the WFC3. These comparisons will be made more uniform in the fall of 2015.
- Figure 5 shows the current astrometric accuracy for the various instruments.

While the HSC represents a tremendous new resource for astronomers, it must be used with care. Unlike SDSS, with a uniform set of filters and all-sky coverage over a substantial part of the sphere, the *Hubble* database consists of tiny pieces of sky using several different cameras, hundreds of filters, and exposure times that range from a fraction of a second to thousands of seconds. Hence the HSC is a *very different type of catalog*. It will require *caution* when making use of it.

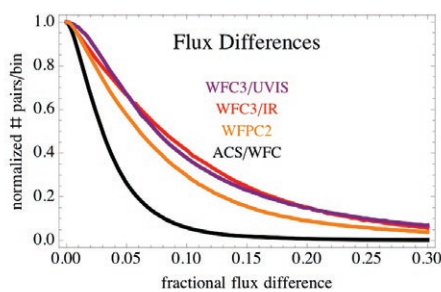


Figure 4: Color-coded photometric comparisons between repeated measurements for the various instruments.

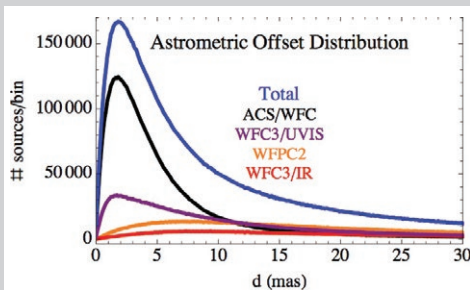


Figure 5: Color-coded astrometric comparisons between repeat measurements for the different instruments. The peak of the distributions for the WFC2 and WFC3/IR occur at higher values primarily due to the larger pixels for these instruments.

Potential users should pay special attention to the “five things you should know about the HSC” (http://archive.stsci.edu/hst/hsc/help/HSC_faq.html#five_things). This website illustrates common artifacts and limitations that can occur. In Figure 6 we highlight one of these “five things,” namely that coverage can be non-uniform. The figure shows a particularly dramatic example, caused by overlapping images and a poor choice of the number of images to require for a match. The lesson is that users should keep the unique characteristics of the HSC in mind. In particular, they should always *look at the relevant images*, rather than just blindly pulling things out of the HSC database.

Catalogs have been a mainstay since the beginning of astronomy. Historical examples include the Messier and Herschel catalogs, and the New General Catalog. More recent examples include 2MASS, *Hipparcos*, and SDSS. Examples of those coming in the future will include the catalogs of the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), *Gaia*, and the Large Synoptic Survey Telescope (LSST).

In many ways the *Hubble* Source Catalog will be unique, first and foremost because of the depth and spatial resolution of *Hubble Space Telescope*. It will also be unique because of the inherent non-uniformity and patchwork nature of *Hubble* observations. This irregularity will require care when developing search criteria. Nevertheless, it is clear that the HSC will be a powerful new tool for research with *Hubble* data, even with its limitations, and will be an important reference for future telescopes, such as *James Webb Space Telescope*, and survey programs, such as LSST.

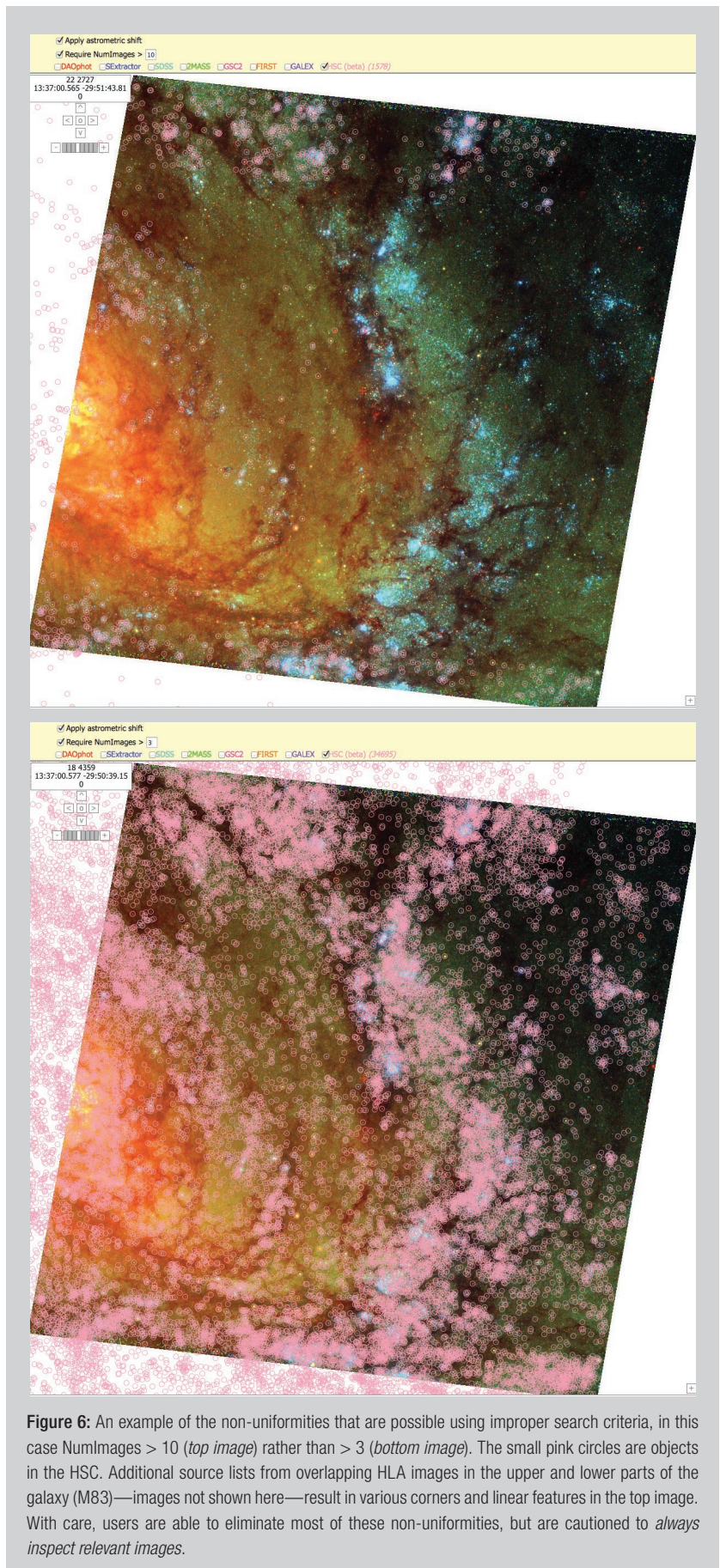


Figure 6: An example of the non-uniformities that are possible using improper search criteria, in this case NumImages > 10 (*top image*) rather than > 3 (*bottom image*). The small pink circles are objects in the HSC. Additional source lists from overlapping HLA images in the upper and lower parts of the galaxy (M83)—images not shown here—result in various corners and linear features in the top image. With care, users are able to eliminate most of these non-uniformities, but are cautioned to *always inspect relevant images*.

Advisory Committee Origins of the Space Telescope Science Institute

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The author is a former assistant associate administrator of NASA's Office of Space Science and Applications and former director of the Space Studies Board of the National Research Council. This article is adapted from a forthcoming book on the history of outside scientific advice to NASA.

Scientific advisory committees have played important roles throughout the entire history of space research. They have provided effective mechanisms for communicating the views of the scientific community to federal science agencies, especially NASA, and for helping agencies obtain expert advice, and those functions have measurably enhanced the quality and productivity of the agencies' programs. A 1976 committee that was charged to examine institutional concepts for the operation of the Space Telescope provides an interesting case study of this advisory process.

In the early 1970s, NASA and space astronomy advocates in the scientific community were trying to build a case for starting development of the Large Space Telescope. While most of the activity focused on design studies for the proposed flight hardware, NASA officials also began to consider approaches for operating the telescope once it could be launched. The mission was expected to have a 10 to 15 year lifetime during which it would operate as a facility that would serve many users and produce unprecedentedly large volumes of data. Thus the post-launch scientific aspects of the program would be formidable and would include activities such as evaluating proposals for observing time, establishing observing priorities, scheduling telescope operations, and generally serving as the primary interface with the scientific community.

Two competing concepts emerged, and they generated lots of heated debate. NASA's initial preference was for scientific operations to be co-located with the engineering control center for the spacecraft and telescope at a NASA facility. This was the strong, basically unyielding, preference of officials at the Goddard Space Flight Center, where management responsibility for development of the telescope's scientific instruments and for flight mission and data operations had been assigned. Outside astronomers could play an advisory role, but Goddard people were convinced that their experience with earlier multi-user astronomy missions, in which NASA had end-to-end control and in which outside astronomers participated as guests, demonstrated that was the way to go.

On the other hand, outside astronomers in the broader scientific community were equally convinced that scientific operations of the telescope should be outside NASA's control. Many in the scientific community felt that NASA could not be trusted to work fairly on behalf of all astronomers or to remain committed to the long-term scientific value of the telescope. So the astronomers' alternative was an independent scientific institute that would be managed by an outside organization, such as a consortium of universities. The concept was not especially new. For example, in 1966 an ad-hoc NASA Science Advisory Committee had recommended establishment of a lunar science institute. That idea subsequently led to creation of the Lunar Science Institute that was initially managed by the National Academy of Sciences through Rice University and then, beginning in 1969, by a new consortium of universities—the Universities Space Research Association. The concept was also familiar to astronomers who had experience with the Association of Universities for Research in Astronomy (AURA) through which the Kitt Peak National Observatory complex of telescopes was managed for the National Science Foundation.

Thus, by the mid-1970s, the terms of a battle were clearly drawn. Would scientific aspects of the telescope's operations be controlled by NASA along with the rest of the telescope's operations—possibly with some advice from participation by the scientific community—or would science operations be separate from the traditional functions of the space mission control center and controlled by an independent scientific organization? Astronomers outside NASA strongly adhered to the latter, and some NASA managers began to warm to that approach as well. But others, especially at Goddard, held fast to the former, NASA-controlled approach. Noel Hinners, who was then serving as Associate Administrator for Space Science, already had his hands full dealing with challenges posed by the program's budget, plus a political fight to gain congressional approval for the program, plus continuing resistance from those astronomers who thought the project was too costly compared to the ground-based facilities with which they had always worked. He didn't need another battle with the scientific community at that time. Consequently, Hinners arranged for the National Academy of Sciences' Space Science Board to

organize a study to examine possible institutional arrangements for the scientific use of the telescope.

Donald F. Hornig, who had just stepped down from being President of Brown University, was selected to chair the study committee. Hornig was a Harvard-trained chemist who had been a group leader in the Manhattan Project and who had served as Science Advisor to President Lyndon Johnson from 1964 to 1969. The 17-person committee (see sidebar) included both astronomers who had experience with space astronomy missions and others who were experienced with the operation of ground-based astronomical facilities.

The committee met for information collection sessions in Washington, DC, and at Goddard, and then they gathered for a two-week work session at the NAS study center in Woods Hole, MA. The luxury of having a study committee together for two straight weeks of discussion and report writing (free from email- and cell-phone distractions!) would be a rare luxury now, but it was not uncommon in the 1960s and 1970s.

The committee's report—"Institutional Arrangements for the Space Telescope"¹—was a remarkably thorough assessment of plans for the Space Telescope (ST),² experience with other space and ground-based observatories, factors relevant to whether an institute was needed, and options for the structure of an institute. The committee's unequivocal core recommendations included the following:

- “* The productive use of the ST depends upon the safe, reliable operation and maintenance of the spacecraft and its associated communications and data-processing systems, and upon the quality of the astronomical research which is conducted with it.
- * Whereas the operation of the ST and its associated systems is best carried out by NASA, optimum scientific use of the ST requires the participation of the astronomical community.
- * An institutional arrangement, which we call the Space Telescope Science Institute (STSI),³ is needed to provide the long-term guidance and support for the scientific effort, to provide a mechanism for engaging the participation of astronomers throughout the world, and to provide a means for the dissemination and utilization of the data derived from the ST.
- * We recommend that the STSI be operated by a broad-based consortium of universities and non-profit institutions... The consortium would operate the institute under a contract with NASA.
- * We recommend that the policies of the STSI be set by a policy board of about ten people representing the public interest, as well as the astronomical community and the broader scientific community. The quality and independence of the policy board is essential to the success of this enterprise.”

The report went on to discuss recommended scientific and operational functions, structure, governance, staffing, facilities, arrangements for interactions with NASA, and location of the institute. NASA largely accepted the Hornig committee's recommendations and after a competition to select an organization to create and manage the institute, NASA selected AURA, and the Space Telescope Science Institute (STScI) was established in 1981. STScI now sits in Baltimore adjacent to the Johns Hopkins University campus and slightly more than a one-hour commute from Goddard. The institute has been enormously successful, something about which both astronomers and NASA officials agree.

The Hornig report is a good example of an advisory effort that met NASA's needs and provided actionable advice that had a significant lasting impact. NASA's Noel Hinners wanted a way to resolve the conflict between Goddard and the astronomy community, he wanted independent guidance on how to maximize the long-term scientific value of the Space Telescope program, and he wanted to be able to build a positive relationship with the community that would shore up their willingness to be advocates for the program. Hinners probably also wanted cover; he had a good idea of what he wanted to do, but having a National Academy of Sciences committee behind him made his future decisions much more palatable. History suggests that he succeeded on all counts.

Members of the Study Committee on Institutional Arrangements for the Space Telescope

Donald F. Hornig (chair)
Michael J. S. Belton
Ralph Bernstein
George W. Clark
Arthur D. Code
W. Donald Cooke
C. Chapin Cutler
George B. Field
John W. Firor
Robert B. Leighton
Edward Ney
Louis Rosen
Vera C. Rubin
Wallace L. W. Sargent
Stephen E. Strom
William F. Van Altena
E. Joseph Wampler

¹National Research Council, "Institutional Arrangements for the Space Telescope: Report of a Study at Woods Hole, Massachusetts, July 19–30, 1976," Washington, DC: The National Academy Press, 1976.

²Following the formal naming of the ST after Edwin Hubble, the acronym "ST" became "*HST*"—for the *Hubble Space Telescope*.

³"STScI" has now replaced the original acronym "STSI."

Webb Status

Rachel Osten,¹ osten@stsci.edu

There were no lazy days of summer for the scientists and engineers working on the *James Webb Space Telescope*! Rather, summertime saw flurries of activity on many different mission fronts.

Meeting mission milestones

The *James Webb Space Telescope* project is still holding steady to its planned launch of the observatory in October 2018. A number of different facets to the observatory are reaching critical points in preparation for launch, and the pieces that make up the observatory are slowly coming together.

Although activity is always occurring on different parts of the observatory, each year leading up to launch has a theme to epitomize the important components of the mission in process that year. *Manufacturing the spacecraft* was the theme for the year 2014, and key advances have been made on several fronts.

Testing of the sunshield at Northrop Grumman commenced, using a full-scale engineering model. This is the largest part of the observatory, expanding to the size of a tennis court when fully unfurled. In July 2014, this full-scale engineering version underwent folding and unfolding tests. Manufacturing of the flight version of individual layers is underway. The sunshield testing and fabrication is described in more detail in a companion article by A. Conti.

A successful critical design review (CDR) of the spacecraft took place earlier in 2014 at Northrop Grumman. As a result, manufacturing the parts that form the spacecraft—such as fuel tanks, gyroscopes, and solar panels—has commenced. The other components of the spacecraft, which provide power and communications for the entire observatory, as well as telescope and image stabilization, also saw significant advancements on the planned timeline.

Preparations are underway for the series of tests that will occur after the next step in the integration of the observatory, when the science instruments get connected to the optics. These tests will occur at the historic Chamber A at Johnson Space Center in 2016. Chamber A is known for its role in testing equipment during the Apollo missions, and was chosen to be the location of the testing of the Integrated Science Instrument Module (ISIM) and the Optical Telescope Element, due to the large size of the chamber, which is needed to accommodate the *Webb* structure (see Figure 1). In July, the chamber was subjected to a cryogenic proof test and a bake-out, in which the temperature inside the chamber was raised in order to drive off any contaminants.

A refurbishment has made Chamber A, the largest cryogenic-optical vacuum test chamber in the world, ready to support future testing of *Webb*'s components. The renovations enable the low temperatures required for testing the combined optics and instruments, the ability to maintain vacuum for the weeks-long durations of the testing, and increase the efficiency of the testing by minimizing the amount of nitrogen and helium coolant required. The ground support equipment for this phase of testing includes sunshield and thermal simulators, a vibration isolator, a center-of-curvature optical assembly, an autocollimating-flat assembly, and photogrammetric cameras.

Testing, take two

With the arrival of the last two *Webb* science instruments in 2013, the ISIM now holds all four science instruments. Some known deficiencies in the flight hardware have already been corrected and the remaining problems will be fixed between the second and third cryo-vacuum test campaigns (CV2 and CV3). To alleviate the degradation experienced by the near-infrared focal-plane arrays, replacement detectors for each near-infrared instrument were manufactured, tested, and certified for flight. The Near Infrared Camera (NIRCam) received its new batch of detectors in November 2013, prior to CV2. Those for the Near InfraRed Spectrograph (NIRSpec), the Near Infrared Imager and Slitless Spectrograph (NIRISS), and the Fine Guidance Sensors (FGS) will be installed into these science instruments by January 2015, well in time for CV3.

Integration and testing is now picking up pace. The ISIM CV2 began in Goddard's Space Environmental Simulator vacuum tank with a functional test at ambient temperature and pressure on June 16, 2014. This was followed



Figure 1: Picture of Chamber A at Johnson Space Center, where cryo-vac tests are set to take place in 2016. The interior of the chamber is as large as a tennis court; the large size is necessary to fit the instruments and mirror assembly for testing. Renovations to the historic chamber, first used to test equipment for the Apollo missions, are underway to prepare it for the long-duration, low-temperature testing to occur as the parts of the observatory come together. Credit: Chris Gunn/NASA.

by evacuation and cool-down to about 40K. CV2 testing spanned 76 days of cold testing followed by approximately 17 days of warm-up and concluding functional tests (see Figure 2).

In almost all respects, the science instruments (SIs) performed very well. Optical testing included alignment with six degrees of freedom, measurements of pupil shear, and an extensive series of focus and wavefront error measurements using both internal and external focus-adjustment mechanisms. The testing also involved a broad range of tests for each SI to characterize performance.

Various tests were successfully run using the Operations Script Subsystem, the commanding system to be used in flight. These scripts were developed at the institute as part of our flight operations work. These tests included the FGS running through its primary functions, from star identification to fine guiding.

With NIRCams newly replaced detectors, a lengthy tune-up of their Application Specific Integrated Circuits (ASICs) was executed. The goal was to configure them for optimal noise, bias, and well depth performance. This process will be repeated in CV3 for the newly replaced detectors in NIRISS and FGS. The new NIRSpec detectors will be installed with previously tuned, spare ASICs.

The testing did reveal some problems; the most serious was a data-flow issue that caused the Instrument Control and Data Handler (IC&DH) to spontaneously reboot when simultaneously receiving interrupt requests from multiple detectors at very high rates. A modification to the flight software addressed the problem, and it did not occur again through the remainder of CV2.

Another problem that occasionally occurred during high data-rate observations was mixing of data originating in separate detectors. Operational constraints are now being established to keep the rates within acceptable limits.

There were two notable issues with the science instruments. The replacement NIRCams detectors performed superbly, but one of them, in module A, drew excessive current and was shut down during most of CV2 to prevent damage. It has now been established that the problem is with the detector itself and it is being replaced.

The second issue was that observations using the NIRISS GR150R grism showed a streak of scattered light that was not present in CV1. Post-CV2 examination of the grating has revealed delamination in a small section of the grism and it is being replaced.

Testing also found some issues with the ground system. In some instances, data from different SIs were combined in the same data file, header keywords were missing, or the data files were not generated at all. Some of these problems have already been addressed and the remaining ones are being investigated.

While the final judgment on CV2 must await a more complete analysis of the data, it is clear that overall the test has been a great success. The important goals of demonstrating SI performance, alignment, and stability appear to have been met. The test team is well positioned to make the final hardware replacements in preparation for CV3, the final thermal-vacuum test campaign at Goddard. CV3 is scheduled to take place in the latter half of 2015.

Webb operations from the ground up

We refer to *Webb* as the successor to *Hubble*, because many of *Hubble*'s ground-breaking discoveries motivate the capabilities of *Webb*. The science operations of *Webb* at the Institute are also rooted in *Hubble*, as they will utilize the experience that engineers and scientists at the Institute have built up in the almost 25 years of *Hubble* operations. There are differences, however, between how *Hubble* operates and how *Webb* will operate. One notable difference is that the flight operations of *Webb* will be controlled from the Institute, in addition to the science operations. (Flight operations for *Hubble* occur at Goddard, with data transmitted to the Institute for dissemination to the science community.) To evaluate the work happening at the Institute for *Webb*'s science operations, the project conducted the Science and Operations Center (S&OC) System Design Review (SDR) on July 14–16, 2014. This review was independent of the *Webb* project and organized by Goddard. The primary focus of this first SDR was S&OC architecture and science operations; a future SDR (in 2016) will focus on flight operations and commissioning. Subsystems reviewed included the project reference database, proposal planning, data management, software for wavefront sensing and control, and operations scripts. By all review criteria, the S&OC received the green light to proceed. Strengths noted by the review committee included the heritage from *Hubble* in designing some of the science operations systems, and the ability to implement new *Webb* software in *Hubble* operations to provide feedback and operational experience in advance of *Webb* operations. A lot of effort was needed from the Institute's *Webb* staff to prepare and execute the review. We commend their efforts.

Preparing the astronomical community for Webb

Although the launch of *Webb* is less than four years away, the *Webb* mission office at the Institute is already preparing the astronomical community to think about the types of transformational science enabled by *Webb*. We perform this outreach through a variety of organized interactions with the community. At major meetings, like the biannual meetings of the American Astronomical Society, we make sure that a wide cross-section of the community hears about the current status of the *Webb* project, and apprise

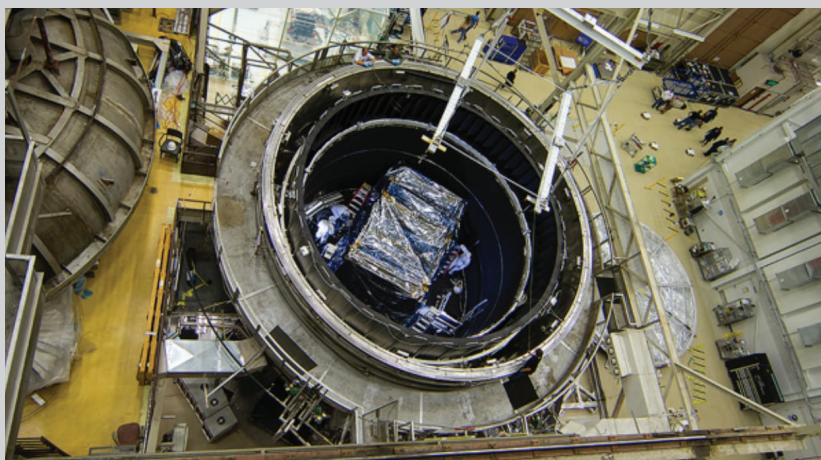


Figure 2: *Webb's* Integrated Science Instrument Module (ISIM) coming out of the Space Environment Simulator (SES) at Goddard Space Flight Center, at the completion of the second cryo-vac test or "CV2" in mid-October. Credit: Mike McClare/NASA.

them of issues about which they can provide input. *Webb* had a booth at the June 2014 AAS meeting in Boston, where we sought feedback on the design of the exposure-time calculator, and conducted a survey concerning optimizing documentation for scientists. A *Webb* town-hall meeting took place at the 225th AAS meeting in Seattle, Washington, and included a timely discussion on January 6 led by scientists at the Institute on policies to optimize community engagement and maximize early science from *Webb*. A webcast of the town-hall is available at <https://www.youtube.com/watch?v=ZTJJAuziywl>.

Webb's highly complex instrument modes, combined with its limited lifetime (as compared to *Hubble*)—a five-year requirement on the mission lifetime and a ten-year goal—has driven a number of discussions about how to maximize the science return of *Webb*. Based on experience with other observatories, it is clear that getting on-orbit data into the hands of astronomers quickly is key to realizing the full scientific potential of the instruments and the observatory. The *JWST* Advisory Committee to the Institute director has advocated for an open-access early release science program to demonstrate the key observing modes of *Webb's* instruments. The planning of the early release science program will be an open process, involving community members, and was announced at the *Webb* town-hall meeting in Seattle.

To engage unique parts of our future user base, we have established a presence at more specialized, regularly occurring meetings. The goal is to seek new perspectives and feedback regarding observing capabilities. In this spirit, we attended the 45th Lunar and Planetary Science Conference (LPSC) in The Woodlands, Texas, in March, where the *Hubble* and *Webb* projects hosted a joint town-hall. We apprised the solar-system community of the status of these two observatories and invited their interest and involvement. We reviewed the status of previous recommendations regarding solar-system observations with *Hubble*, and solicited further input. Our presence at the 46th Division of Planetary Science (DPS) meeting in November in Tucson, Arizona included a topical session focusing on reports from ten community-based groups in a joint *Webb* town-hall meeting. The white papers being prepared by these groups will describe prospective case studies of different types of solar-system science investigations with *Webb*. The joint *Webb* town-hall meeting held at DPS was recorded; the presentations and a recording of the session can be found at <http://www.stsci.edu/jwst/science/jwst-solar-system-meetings-docs>. A booth provided an additional point for interaction between *Webb* project members and the solar-system community.

Informing the community about data analysis software being developed for *Webb* is an important component of preparing the astronomy community to do science with *Webb*. The tools to be used for data exploration will be written in the PYTHON programming language, and packaged as part of the ASTROPY software toolkit (Robitaille et al. 2013, A&A volume 558, page A33). We are initiating a series of events which will familiarize future *Webb* users with ASTROPY and tools being developed specifically for *Webb* science analysis. The Seattle AAS meeting featured a Sunday morning ASTROPY tutorial for those seeking more information on how to use the ASTROPY software and a description of recent developments. From May 6–8, 2015, the Institute will host a User Training in *JWST* Data Analysis meeting (http://www.stsci.edu/institute/conference/ut_jwst_da/). The 2½ day meeting will introduce data analysis tools to the *Webb* user community. It will serve to familiarize novice PYTHON users with ASTROPY, and follow the workflows of several example data analysis use cases. There will be a heavy emphasis on hands-on use of the tools available, as well as opportunities for feedback and suggestions for improvement. Both the AAS ASTROPY tutorial and User Training event will become annual occurrences.

The Single-Object Slitless Spectroscopy Mode of *Webb*'s NIRISS Instrument

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The *James Webb Space Telescope*'s Near Infrared Imager and Slitless Spectrograph (NIRISS) will offer a number of innovative observing modes, including single-object slitless spectroscopy (SOSS). This mode is optimized for spectroscopy of transiting exoplanet systems around nearby (and thus often bright) stars. It operates in the wavelength range between 600 and 2800 nm, which includes strategic spectral features from molecules such as O_2 , H_2O , CO_2 , and CH_4 , which are either common or expected in the atmospheres of exoplanets.

The SOSS mode is enabled by a grism that generates two usable orders of cross-dispersed spectra of a single target. A third order is also present, albeit at a low signal level. Order 1 covers the wavelength range ~ 850 – 2800 nm at a resolving power $R = 700$, while the usable part of order 2 covers ~ 600 – 1300 nm at $R = 1400$. Figure 1 illustrates the location and shape of point source spectra created by the SOSS grism.

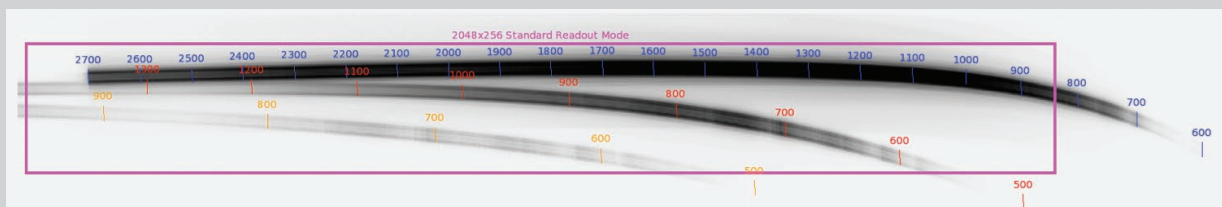


Figure 1: Simulation of the appearance of a SOSS spectrum of a M3V star. Grayscale indicates intensities in logarithmic units. Wavelengths in nm are indicated in blue, red, and orange for spectral orders 1, 2, and 3, respectively. The magenta box outlines the portion of the spectrum read out by the default SOSS detector window.

A unique feature of the SOSS mode is the wide shape of the radial distribution of its light in the direction perpendicular to the dispersion. This is commonly called “the cross-dispersion point spread function” (cdPSF). For most spectroscopy modes on the *Webb* telescope, the aim is to provide a good spatial sampling of the sky, in which case a typical full width at half maximum (FWHM) of cdPSFs is 2–3 detector pixels. In contrast, the width of the SOSS cdPSF is ≈ 35 pixels, with $FWHM \approx 25$ pixels(!). The appearance of the SOSS cdPSF is illustrated in Figure 2.

The shape of the SOSS cdPSF is caused by a weak defocussing lens built into the SOSS grism. It produces two important benefits to spectroscopic studies of exoplanet systems, which typically require data with very high signal-to-noise ratio (S/N)—of order 10^4 – 10^5 ! First, the wide cdPSF allows observations of bright targets whose spectra would be saturated on the detector in the absence of the lens. Second, it mitigates the need to dither¹ the telescope during SOSS observations. For most observing modes on *Webb*, the small PSFs of telescope dictate a need for dithering, to circumvent the effects of bad detector pixels. However, the combination and calibration of dithered data requires an adequate knowledge of the relative sensitivities of every individual detector pixel. Achieving this is impractical for the S/N required for the science cases that motivate the SOSS mode. Thus, the wide cdPSF of the SOSS grism

¹“Dithers” are small-angle maneuvers of the telescope between individual exposures. Their main purposes are to eliminate the effect of bad detector pixels and/or to improve the effective spatial resolution of the resulting data.

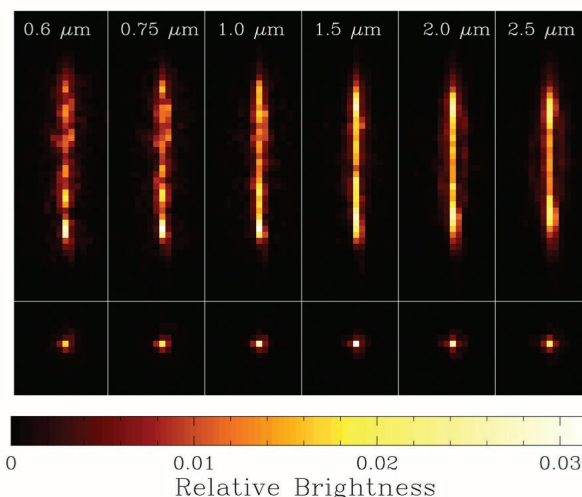


Figure 2: Simulation of the SOSS cdPSF (the PSF in the direction perpendicular to the dispersion). The top panels depict simulations at the wavelengths indicated with the weak lens in place, while the bottom panels do so *without* the weak lens. The features shown in these simulations have been confirmed by actual observations taken during the cryogenic vacuum tests at Goddard Space Flight Center. (Figure courtesy of David Lafrenière, Université de Montréal).

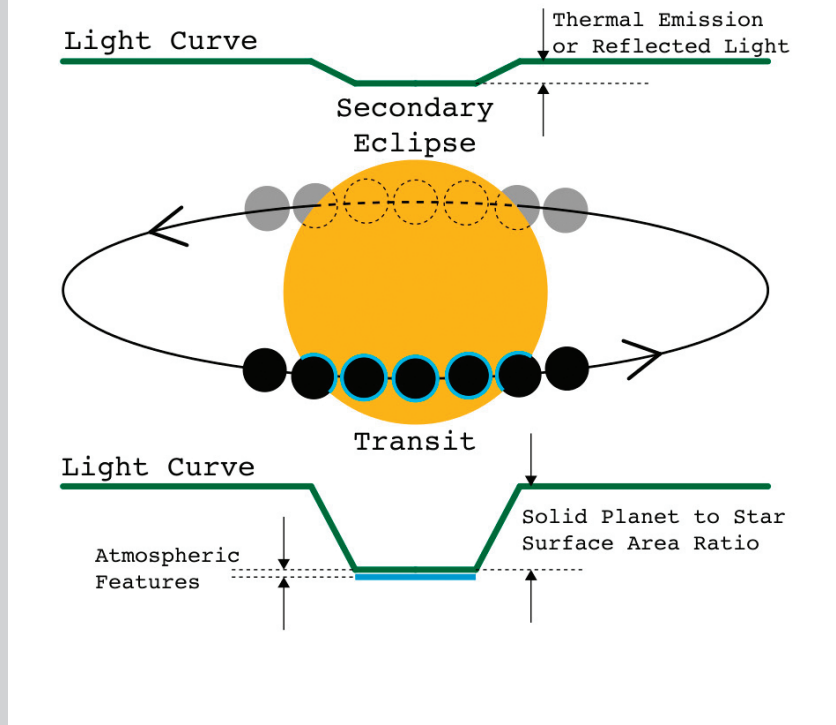


Figure 3: Illustration of star-planet configurations that cause transits and secondary eclipses. The star is represented by a yellow circle, while the planet is shown in black when in front of the star and in gray when on the far side of the star. The planet's atmosphere is shown in light blue, when the planet is in front of the star. Light curves for transits and secondary eclipses are illustrated in green at the bottom and top, respectively.

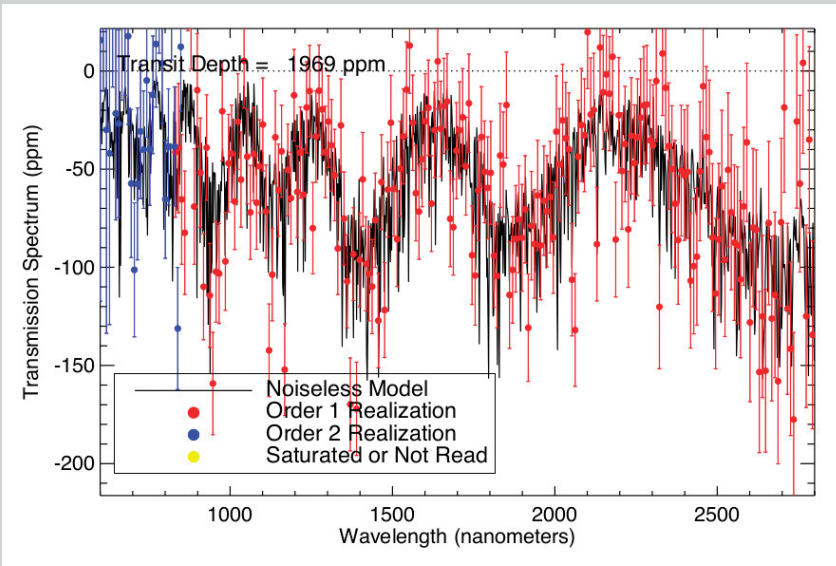


Figure 4: Simulation of an Earth-size “water world” planet with half the Earth’s density, observed with NIRISS/SOSS. We stack five transits and assume $J = 8.0$ mag for a late M star with a temperature of 3200 K and a radius of 0.2 Sun radii orbiting in the habitable zone. This target requires 32 hours of clock time under the assumptions of an overhead of 45 minutes (for the telescope slew, target acquisition, and detector stabilization) and spending twice as much exposure time out of transit as in-transit. (Planet atmosphere model courtesy of Eliza Kempton, Grinnell College).

avoids dithering and allows dwelling on the same detector pixels during long exposures. The result is uniquely high relative photometric accuracy.

Characterization of exoplanet atmospheres with SOSS

We envision that the SOSS mode will advance the study of three main types of exoplanets: Jupiter-like planets, super-earths, and possibly earth-like planets. Super-earths are planets with masses between that of the earth and about eight times that, with a density indicative of a rocky body.

The choice of targets will mainly be limited by observational factors. One condition is that planets pass directly in front of their stellar host—a transit event—and/or that planets be completely eclipsed by their host—a secondary eclipse (see Figure 3). Both conditions require that the orbit of the exoplanet be almost edge-on as seen from Earth, which, for a randomly distributed population of planetary systems, occurs less than 5% of the time.

The physics achieved in transit events will differ slightly from that in secondary eclipses. For transits, only planets with a significant atmosphere can leave an observational spectral imprint: the starlight grazing through the small crescent of the atmosphere is transmitted with varying strengths, depending on the chemical composition of the upper planet's atmosphere. For secondary eclipses, light is incident at 90 degrees, which allows a deeper probe into the atmosphere of a planet. In the case of rocky planets, the light then actually reaches the solid surface before being reflected back at us, thus allowing a measurement of the planet's albedo.

Another important limitation on transit events is the scale height of the exoplanet atmosphere: large scale heights are synonymous with large effective-radius changes as a function of wavelength, and hence larger, more observable, signals. The atmospheric scale height is proportional to temperature and inversely proportional to surface gravity and molecular weight. For example, an atmosphere of hydrogen has a larger scale height than that of nitrogen, by the ratio of the molecular weights, $28/2 = 14$. Another example is that a massive planet with high surface gravity—say $\log g = 4.0$ —has a smaller scale height than Earth— $\log g = 3.0$ —by a factor of 10. Thus, the exoplanets with the strongest expected spectral signatures are low-density, hydrogen-rich, high-temperature planets.

The final limitation is photon statistics. For hot Jupiters, with the largest signal, the strength of spectral features expected in transmission spectra are less than 1000 parts per million (ppm). Detecting these features at $S/N = 10$ requires spectra of the stellar host with a $S/N > 10,000$. These constraints mean that targets need to be rather bright, ideally $J < 10$ mag.

The wealth of new exoplanets found by the transit method has made the study of their atmospheres a reality. The likely most numerous type of exoplanets that *Webb* will observe are gas giants. Observing such Jupiter-like exoplanets at a variety of distances and around various types of star hosts will allow the discovery of trends that may exist between the chemistry of a planet's atmosphere and the planet's temperature or the host-star type. The effect of the metal abundance will also be studied.

Super Earths are another type of high-profile targets. These are currently the closest observable analogs to Earth and are at the characterization limit with *Hubble*. Two good examples are GJ 1214b and HD 97658b. Models showed that hydrogen-rich or even water atmospheres would be detectable with *Hubble*, using the grism mode of the near-infrared channel of the Wide Field Camera 3 (WFC3). While the WFC3 observations were successful, both of these super Earths unfortunately turned out to exhibit relatively featureless transmission spectra, likely because of high-altitude haze or dust in their atmospheres (Kreidberg et al. 2014; Van Grootel et al. 2014; Knutson et al. 2014).

The upcoming all-sky photometric survey by the *Transiting Exoplanet Survey Satellite*, slated for launch in 2017, will likely find new super Earth targets of sufficient brightness to be observed with *Webb* (see tess.gsfc.nasa.gov). It may even identify Earth-like hosts. If such targets are sufficiently bright ($J < 8$ mag), then it will be possible to characterize the compositions of their atmospheres with the SOSS mode of NIRISS. A simulation of a SOSS observation of an Earth-size “water-world” planet is illustrated in Figure 4. To be successful, such observations will require uninterrupted observations of several transit events, as well as a deep understanding of the instrumental systematic noise.

The SOSS mode of NIRISS promises to be a big leap forward in the quest for spectra of Earth analogs. It may possibly detect water, methane, and/or CO₂ absorption bands, if such properties exist among planets around nearby sufficiently bright stars.

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NIRISS is provided to the *Webb* project by the Canadian Space Agency (<http://www.asc-csa.gc.ca/eng/satellites/jwst/contribution.asp>). René Doyon (Université de Montréal) is the Principal Investigator. The prime contractor is COM DEV Canada. More information about NIRISS is available on the NIRISS website at the Institute (<http://www.stsci.edu/jwst/instruments/niriss>).

Webb Sunshield Unfolds

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One of the most visually striking subsystems of NASA's *James Webb Space Telescope* is its stunning sunshield. Separating the observatory into a warm, sun-facing side and a cold, anti-sun side, a full-scale mockup of the sunshield subsystem has undergone a deployment test. Conducted by Northrop Grumman in Redondo Beach, California, this test made use of a flight-like Engineering Model (EM) known as the Integrated Validation Article (IVA) to validate the folded configuration of the sunshield and its deployment sequence. The current test involved unfolding and separating the five EM sunshield layers for the first time. The IVA performed flawlessly, and provided key insights into how the actual deployment will take place when *Webb* launches in 2018.

The tennis-court-sized sunshield, which is the largest part of the observatory, will be folded around the *Webb* telescope's mirrors and instruments during launch. As the telescope travels to its operational orbit 1.5 million kilometers from earth, it will receive a command to unfold and separate the layers of the sunshield. The sunshield will reduce the 300 kilowatts of solar power absorbed on the sun-facing side of the observatory to less than 1 watt flowing to anti-sun side. This trickle of heat is driven by a 300K temperature drop across the sunshield's enormous thermal impedance.

During operations, the primary-mirror structure and the instrument payload will radiate their heat to space and cool to a stable equilibrium temperature of about 40K.

The three-day sunshield test, which took place in July 2014, demonstrated the validity of the sunshield-folding design, its stowed configuration for launch, and validated the deployment process. Under the supervision of engineers and technicians, the five IVA sunshield membranes unfolded in about 20 hours. On orbit, the sunshield will take about 72 hours to unfold—with no human supervision required.



Figure 1. Picture of the full-scale sunshield model after the first successful unfolding test. This is an engineering version of the five-layered sunshield, pictured during tests at Northrop Grumman in July 2014. Manufacturing of the flight versions of individual layers is occurring in tandem. (Credit: NASA/Chris Gunn.)

To simulate deployment conditions, engineers developed a clever way to reduce friction by resting the layers on a structure of metal beams covered by plastic. This simple and yet ingenious solution is clearly visible in Figures 1–3 and in a time-lapse video that documented the 20-hour deployment test (<https://www.youtube.com/watch?v=PVAe90vca5Q>). The current test is one among many that serves to validate the sunshield design and inform sunshield and observatory assembly processes. This particular test was aimed at validating our understanding of membrane folding and unfolding and tensioning approaches.

The sunshield's membrane layers, each as thin as a human hair, are made of Kapton—a tough, high-performance plastic coated with a reflective metal. NeXolve Corporation, a Northrop Grumman subcontractor, is manufacturing the flight sunshield layers at their facilities in Huntsville, Alabama. The five flight layers will be delivered to Northrop Grumman in 2016, when extensive testing will continue, followed by integration of the sunshield with the rest of the observatory.

Tests like the sunshield IVA are an essential part of the *Webb* program. The observatory is complex, and direct verification of the observatory models is an essential aspect of its development.



Figure 2. Northrop Grumman engineers during the deployment test. (Credit: Northrop Grumman/Alex Evers.)



Figure 3. Northrop Grumman engineer Tony Yu during the deployment test. (Credit: Northrop Grumman/Alex Evers.)

Exoplanet Investigations with *Webb*

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Characterizing planets orbiting stars beyond the sun—exoplanets—is one of the scientific frontiers pioneered using *Hubble* observations. When *Webb* becomes operational, the current *Hubble* results will be expanded to an astonishing degree—far more than would be expected based on the increase in aperture. *Webb*'s sensitivity in the infrared, and especially its infrared spectroscopic capability, will be a boon to exoplanetary science. While we await *Webb*, exoplanetary astronomers are using *Hubble* with increasing success and impact.

Spectroscopy of exoplanetary atmospheres

The atmospheres of exoplanets, rather than their interior structure, are usually the aspect most amenable to observations. Understanding the heavy-element content and temperature structure of exoplanetary atmospheres is crucial for testing our ideas concerning the formation and evolution of planetary systems. Heavy elements in massive planets can be diluted by the gravitational attraction of copious molecular hydrogen gas during planet formation. Low-mass planets attract and hold less molecular hydrogen, so their heavy elements will be less diluted by accretion. Moreover, low-mass planets can acquire their atmospheres by outgassing, rather than accretion. The relative amount of ices versus rock that constitute low-mass planets will vary depending on where in the protoplanetary disk they form, and that diversity will affect their atmospheric composition. We therefore expect an overall inverse relation between planet mass and the heavy-element content of exoplanetary atmospheres, with quite varied compositions for outgassed planets such as super-Earths. Because carbon and oxygen are major building blocks of molecules in giant-planet atmospheres, diversity in giant-planet composition can also occur during formation, via a gradient in the carbon-to-oxygen ratio of the disk (Oberg 2011).

The first step on the quest to understand the composition of exoplanetary atmospheres was taken more than a decade ago, with the detection of atomic sodium in the atmosphere of the transiting exoplanet HD 209458b (Charbonneau et al. 2002), using *Hubble*'s Space Telescope Imaging Spectrograph (STIS). Atoms or molecules in the atmospheres of transiting planets absorb starlight as they transit (pass in front of) their star (Figure 1). Subsequent *Hubble* transit spectroscopy used the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) to make detections of both water vapor and methane (Swain et al. 2008). The NICMOS detections have been challenged and debated (Gibson et al. 2011; Waldmann et al. 2013), and NICMOS is no longer operational. However, as far as water vapor is concerned, the reliability of the NICMOS results is moot, given the advent of the spatial scan mode using Wide Field Camera 3 (WFC3).

In a large Cycle-18 program (PI: Drake Deming), we began to use spatial scans with WFC3 for transmission spectroscopy of giant exoplanets. Because the exoplanets that we probe orbit relatively bright stars (typically, $V = 7\text{--}11$), short exposures are required in staring mode. Furthermore, the time

required to read the detector and transfer the data makes staring-mode observations inefficient. By contrast, the spatial-scan mode spreads starlight over many pixels in the direction perpendicular to dispersion, and thereby allows much longer exposures without saturating. Spatial scanning has improved the efficiency of exoplanet spectroscopic observations by up to an order of magnitude, depending on the stellar brightness. Moreover, the WFC3 detector has a more uniform response than the NICMOS detector, and detecting water absorption in the WFC3 spectra of transiting planets has proven to be a robust process. Several independent groups have succeeded, with consistent results (Deming et al. 2013; Huitson et al. 2013; Mandell et al. 2013; Wakeford et al. 2013; McCullough et al. 2014; Crouzet et al. 2014).

Current frontiers

There are two current frontiers in transmission spectroscopy of transiting exoplanets using *Hubble*'s WFC3. Both of these frontiers will benefit enormously from *Webb*, because *Webb*'s spectroscopic resolving power and sensitivity will be much greater than *Hubble*'s. Nevertheless, the current *Hubble* capability will allow us to make significant progress prior to the *Webb* launch.

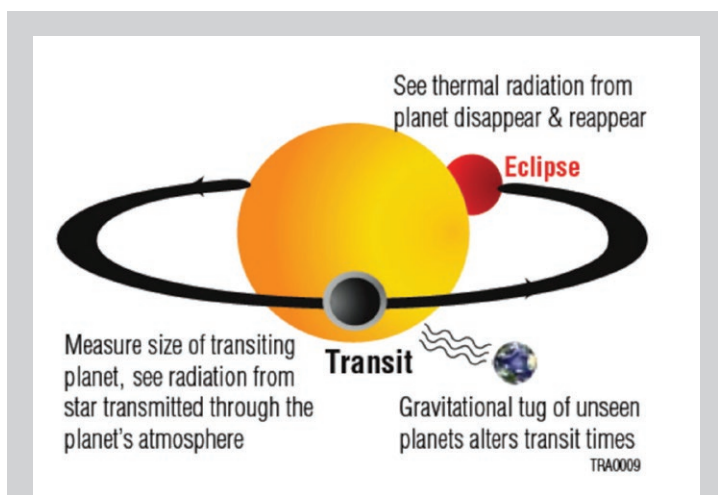


Figure 1: Geometry of exoplanetary transmission spectroscopy. When the planet passes in front of the star as seen from earth, weak absorption features are imposed on the stellar spectrum as star light is transmitted through the annulus of the exoplanetary atmosphere.

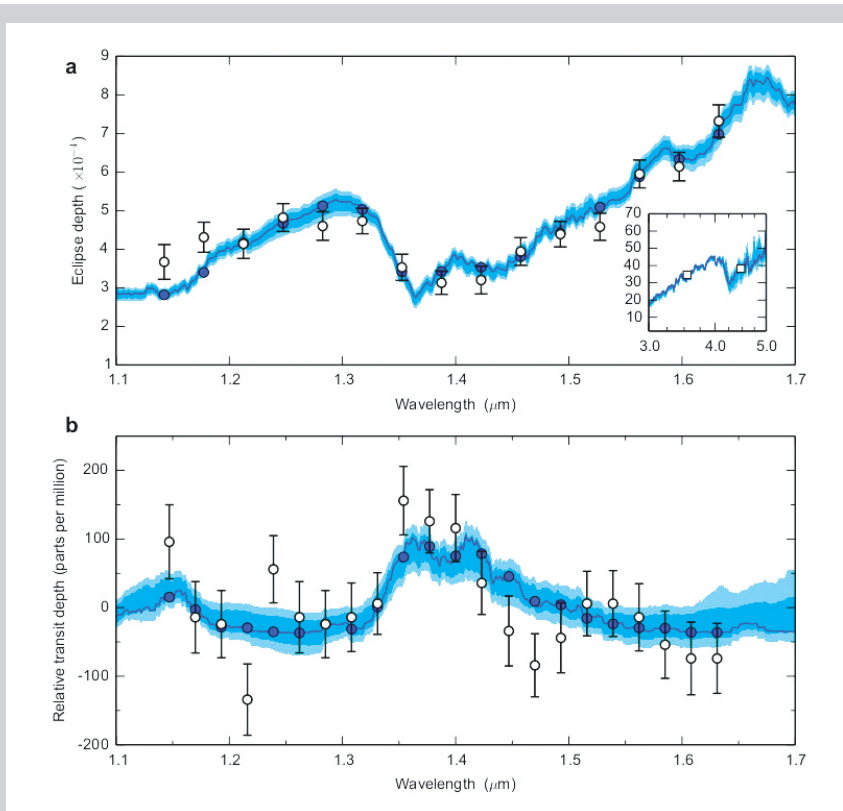


Figure 2: *Hubble* WFC3 spectrum of water vapor absorption in the hot giant transiting planet WASP-43b, from Kreidberg et al. (2014a). The *top panel* shows the spectrum emitted by the star-facing hemisphere of this tidally locked planet (the inset shows *Spitzer* photometry). Prominent water vapor absorption is evident in the WFC3 spectrum, with a bandhead near 1.35 microns. The *lower panel* shows the WFC3 transmission spectrum, i.e., the result of absorption as star light passes through the exoplanetary atmosphere. In the *lower panel*, absorption increases upward—the convention for transmission spectroscopy makes the spectrum appear upside-down. This combination of transmission and emission spectroscopy permits deriving water vapor abundance simultaneously with the temperature structure of the atmosphere.

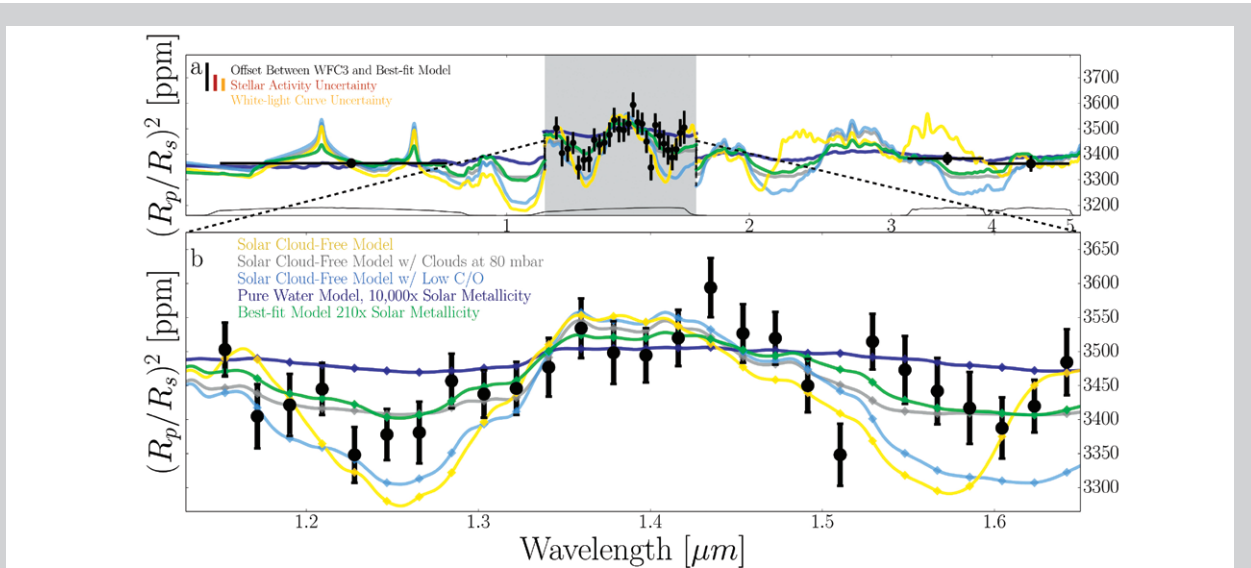


Figure 3: HAT-P-11 transmission spectrum derived by WFC3 observations, reported by Fraine et al. (2014). The *top panel* shows the apparent transit radius of the planet versus wavelength from the optical to the mid-infrared, including the radius measured using *Kepler* (optical) and *Spitzer* (mid-infrared) transits. The points near 1.4 microns are the WFC3 transmission spectrum, expanded on the *lower panel*. The best-fit model (green line) has an overall heavy-element abundance of 190 times the solar value.

One frontier is to obtain both transmission and emission spectroscopy on a given planet, and thereby derive a quantitative water abundance with maximum confidence. Emission spectroscopy refers to the capability to measure the emergent spectrum of the planet by exploiting the secondary eclipse, when the planet passes behind the star. In that case, subtraction of the in-eclipse spectrum of the system (planet hidden) from the out-of-eclipse spectrum (planet contributing) yields the spectrum of the planet alone.

Having both transmission and emission spectroscopy makes it possible to derive abundances of the absorbing species, simultaneously with the temperature structure of the planetary atmosphere. Although longitudinal variations in temperature and abundance are possible across the disk of the exoplanet, measuring the phase curve of hot planets like WASP-43b (Stevenson et al. 2014) helps to constrain those variations. Figure 2 shows WFC3 transmission and emission spectroscopy of the hot giant exoplanet WASP-43b, measured in a Cycle-21 program (PI: Jacob Bean). In this case, the combined measurements also include photometry of the secondary eclipse using *Spitzer*. This combination of *Hubble* plus *Spitzer* data allowed Kreidberg et al. (2014a) to deduce a close-to-solar oxygen abundance for this giant planet.

Interestingly, it is easier to make this measurement for hot giant exoplanets than for giant planets in our own solar system. The latter are sufficiently cold that water vapor condenses out of their atmospheres and is sequestered at depths where it is difficult to observe using spectroscopy of the reflected or emitted radiation from the atmosphere.

A second frontier for WFC3 is to push the water-vapor detections to smaller planets, even to super-Earths. An intense Cycle-21 effort (PI: Jacob Bean) to measure water vapor in the atmosphere of the transiting super-Earth GJ 1214b (2.7 Earth radii) achieved astonishing sensitivity—a precision better than 30 parts per million—but found a flat spectrum. Similar high-sensitivity observations of the atmospheres of the exo-Neptune GJ 436b (4.0 Earth radii) and the super-Earth HD 97658b (2.2 Earth radii) also showed flat WFC3 spectra (Knutson et al. 2014a, b). The atmospheres of these planets may be sufficiently cloudy to block molecular absorption, or some of them could have hydrogen-poor atmospheres with small scale heights.

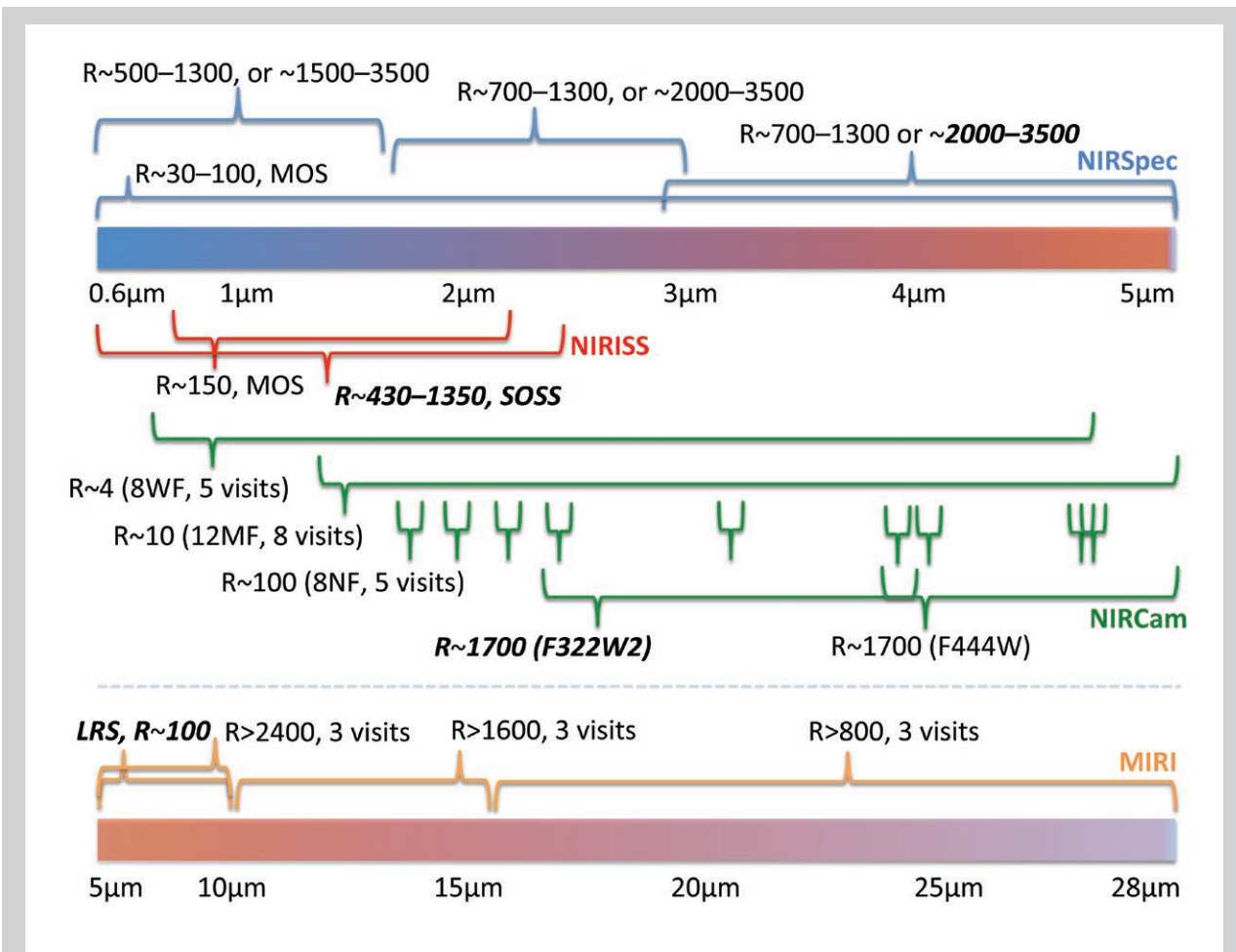


Figure 4: Potential *Webb* observing modes for a hot Jupiter orbiting a bright star, from Beichman et al. (2014). This is the result of a community workshop to plan spectroscopic observing strategies for the brightest and most observable transiting exoplanets. Note that wide spectral coverage that will be possible using *Webb*.

While several small planets seem to be cloudy, at least one—the exo-Neptune planet HAT-P-11b (4.3 Earth radii)—has a clear atmosphere above the level of about one millibar of pressure. The spectrum of that planet shows prominent water absorption, shown in Figure 3, from Fraine et al. (2014). From these WFC3 plus *Spitzer* observations, Fraine et al. concluded not only that the atmosphere is relatively clear, but also that its most likely heavy-element content is about 200 times the solar value. Even though the error range is large—from 1 to 700 times solar—the results are broadly consistent with expectations from the core-accretion model of planetary formation.

Although exoplanetary clouds are interesting in their own right, they are also frustrating because they mute the signatures of molecular absorption and make it much harder to determine the hydrogen content and atmospheric chemistries. An important role for *Hubble* is to establish which exoplanets have high cloud decks, so we can focus *Webb* on those with the clearest atmospheres and deepest absorption features in their spectra. One sensitive way to do this is to measure the optical transmission spectrum, and look for increasing absorption in the blue, due to scattering by small haze particles. A Cycle-22 program (PI: Björn Benneke) will probe other Neptune-sized exoplanets such as GJ 3470b (4.1 Earth radii) in both the optical and infrared (STIS and WFC3). That program will extend the water vapor measurements to super-Earths such as 55 Cnc *e* (1.9 Earth radii), and the Earth-mass planet Kepler 138d.

Webb spectroscopy

Hubble's WFC3 detects primarily water vapor, with little sensitivity to other molecules. However, *Webb* will be much more panchromatic, and will have much greater spectral resolving power. *Webb* will enable abundance measurements in both oxygen- and carbon-containing molecules, such as water, methane and carbon monoxide, with simultaneous constraints on the atmospheric temperature profiles. Recently, powerful methods have been developed (Benneke & Seager 2012; Line et al. 2013; deWit & Seager 2013) to retrieve molecular abundances, cloud properties, and atmospheric temperature structure in an optimal way. Therefore, we are poised to make maximal use of the *Webb* data. *Webb* photometry will not only be more precise than *Spitzer*, but *Webb* will also offer spectroscopy over large swaths of wavelength. Figure 4 (from Beichman et al. 2014) summarizes the many modes whereby *Webb* will be able to observe spectra of transiting exoplanets, and simulation of future exoplanet spectra to be obtained by *Webb* is ongoing.¹

We expect *Webb* to determine accurate molecular abundances and atmospheric temperature profiles for a large sample of transiting exoplanets, from hot Jupiters to super-Earths. Not only will the *Webb* observations reveal their individual properties, they will also transform our understanding of planetary system formation and evolution.

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The Births of Supermassive Black Holes

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The recent discovery of $10^9 M_{\text{sun}}$ black holes (BHs) in massive galaxies at $z \sim 7$, less than a Gyr after the big bang, poses one of the greatest challenges to current paradigms of cosmological structure formation, because it is not known how they became so massive at such early times. Structure formation is thought to be hierarchical, with small objects at high redshifts evolving into ever more massive ones by accretion and mergers over cosmic time. For this reason, it is generally thought that supermassive BHs (SMBHs) grew from much smaller seeds at earlier epochs. One leading candidate for the origin of SMBHs is the collapse of 100–300 M_{sun} Population III (Pop III) stars in primordial halos, or small pre-galactic structures, at $z \sim 20$, or 200 Myr after the big bang. In this scenario, the nascent BH must accrete continuously at the Eddington limit to reach a billion M_{sun} by $z \sim 7$.

But this picture is problematic for several reasons. First, these BHs are “born starving” because the progenitor star evaporates the cloud that gave birth to it. They cannot grow until accretion flows are restored 50–100 Myr later (Whalen et al. 2004). Second, x-rays from the BH tend to disperse the infall once accretion begins, because the potential well of the halo in which the BH resides is too shallow to retain the gas (Park & Ricotti 2011; Johnson et al. 2013). These delays cost the BH crucial e-folding times in exponential growth it needs to become supermassive by $z \sim 7$. Furthermore, Pop III BHs below $\sim 50 M_{\text{sun}}$ are often born with natal kicks that eject them from their halos, and thus their fuel supply (Whalen & Fryer 2012). Their large ejection velocities exile them to the low-density voids between galaxies because they are too fast to be captured by other halos until much later times.

Another path to SMBH seed formation may be catastrophic gas collapse in small, hot, dead protogalaxies at $z \sim 10$ –15. In this scenario, primordial halos conglomerate into a primeval galaxy in the presence of a strong ultraviolet (UV) background that sterilizes them of H_2 , so they cannot form stars. The protogalaxy is thus composed of pristine gas (or baryons), and when it reaches a mass of $\sim 10^8 M_{\text{sun}}$ its virial temperature rises to $\sim 10^4$ K, which activates atomic line emission by hydrogen, which cools it rapidly. Line cooling in turn triggers catastrophic baryon collapse, with central infall rates that can exceed $0.1 M_{\text{sun}} \text{ yr}^{-1}$. Such rates can build up 100,000 M_{sun} Pop III stars in less than 100 Kyr, most of which collapse to BHs without incident at the end of their lives and become SMBH seeds. Recent calculations show that radiation from such stars cannot halt accretion onto themselves, so the BH is born in a high-density environment in which it can rapidly grow (Johnson et al. 2012). The more massive protogalaxy can retain the fuel supply of the BH once it does emit x-rays, because gas heated by the x-rays is not hot enough to fully expand out of the greater depths of its gravitational potential well. Although these SMBH seeds are born later, and therefore have less time to reach $10^9 M_{\text{sun}}$ by $z \sim 7$, they accrete gas at much higher rates because of their much larger masses:

$$\dot{M}_{\text{BH}} = \frac{4\pi\rho_{\infty}G^2M_{\text{BH}}^2}{c_{\infty}^2 + v_{\text{rel}}^2},$$

where ρ_{∞} and c_{∞} are the density and sound speed of the flow in the vicinity of the black hole and v_{rel} is the velocity of the BH relative to the local flow.

Supercomputer models of the formation and collapse of a protogalaxy that is being rapidly cooled by Lyman-alpha emission from hydrogen at $z \sim 15$ show that central infall flattens into a large disk that in some cases is prone to fragmentation into several very massive clumps, as we show in Figure 1b. In other cases the disk remains stable and grows just one supermassive star at its center. It is clear that if radiation from the star fails to halt accretion, it can reach tens of thousands of solar masses in the time required for the protostar to settle onto stable nuclear burning. But several important questions remain to be answered:

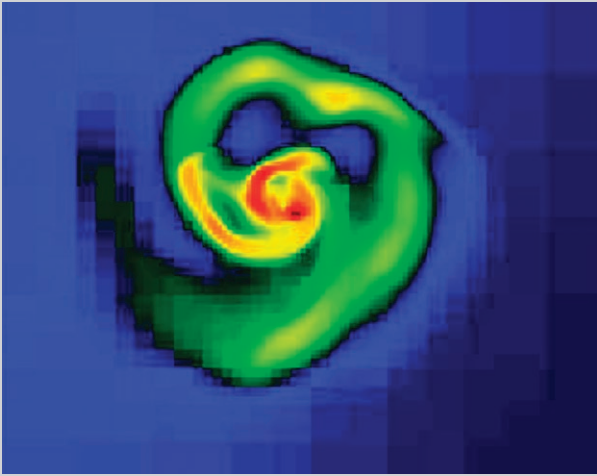


Figure 1a: The collapse of gas into an accretion disk around a supermassive star at the center of a rapidly cooling protogalaxy at redshift $z = 15.4$. The box size is 2000 AU by 2000 AU.

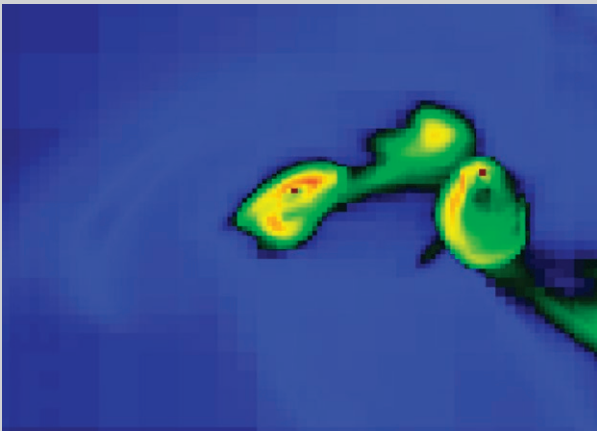


Figure 1b: The fragmentation of the disk due to a thermal instability into supermassive clumps. Each of these clumps could become a supermassive Pop III star.

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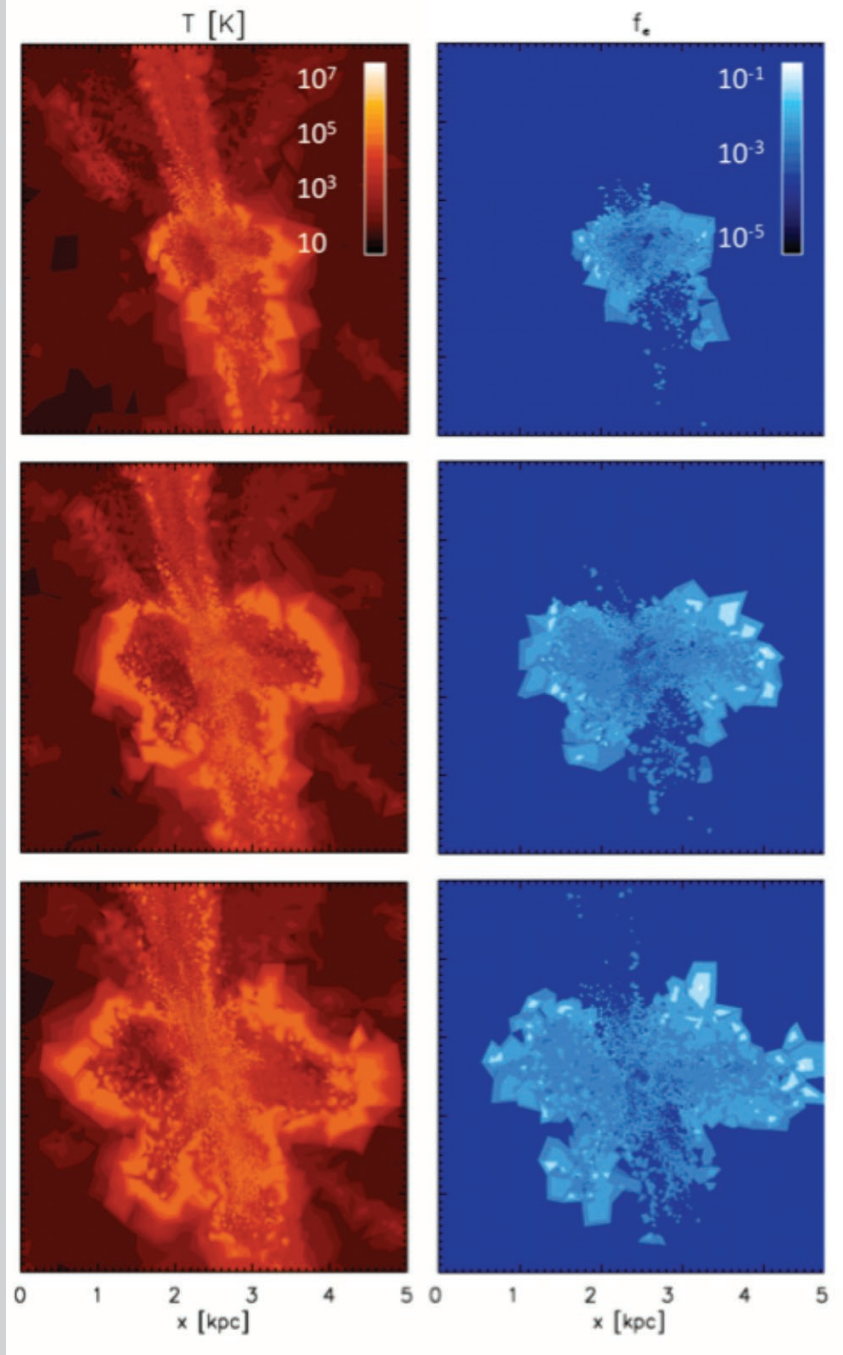


Figure 2: The destruction of a $1.4 \times 10^8 M_{\text{sun}}$ protogalaxy by a supermassive Pop III supernova. *Left panel:* gas temperatures. *Right panel:* electron mass fractions. From top to bottom the times are 10, 25 and 50 Myr, respectively.

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1. How does the supermassive star evolve under ongoing accretion, and what determines its ultimate fate? Does it collapse to a BH or can it explode?
2. After the birth of the BH, can it accrete gas at nearly the Eddington limit even with radiative feedback from its x-rays?
3. At what central BH mass do its x-rays break out into the intergalactic medium? Can UV from recombinations in the vicinity of the BH be redshifted into the near infrared (NIR) today and be detected by *Webb* or the *Wide-Field Infrared Survey Telescope (WFIRST)*?
4. Is the birth of this primeval quasar accompanied by a Pop III starburst in the young galaxy? X-rays from the BH can catalyze the rapid formation of H_2 deep in the halo, triggering a bout of Pop III star formation that would easily distinguish this galaxy from its less rapidly evolving neighbors.

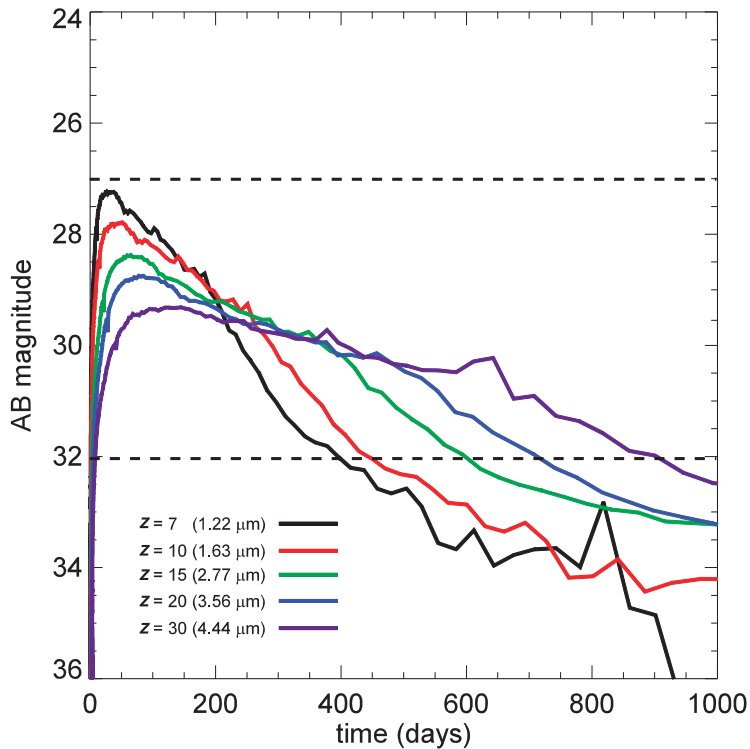


Figure 3: NIR light curve for a 10^{55} erg Pop III supernova. The horizontal lines at AB mag 27 and 32 mark the detection limits of the *WFIRST* High Latitude Survey and *Webb*, respectively. The *WFIRST* 5 sq. degree Supernova Survey Deep Field will go to AB mag 29+ and capture these events at $z > 15$. The *Webb* photometry limit of AB mag 32 corresponds to exposure times of $\sim 10^5$ sec, or about a day.

Additional numerical simulations are now under development to answer these questions. But in partial answer to the first one, it is now known that some supermassive Pop III stars can die in the most energetic thermonuclear explosions in the universe. A general relativistic instability in Pop III stars over a narrow range in mass at $\sim 55,000 M_{\text{sun}}$ can trigger explosive He burning that releases 10^{55} ergs (the energy of 10,000 Type Ia supernovae) and completely unbinds the star (Chen et al. 2014). New simulations show that such explosions can completely destroy the protogalaxies that host them (Figure 2; Johnson et al. 2013; Whalen et al. 2013). Light curves for these events calculated at Los Alamos with the RAGE and SPECTRUM codes reveal that they will be visible to the next generation of NIR missions (Figure 3; Whalen et al. 2013). *Webb* and *WFIRST* may soon detect the most powerful explosions in the universe, and thereby the births of SMBHs.

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Barbara A. Mikulski Archive for Space Telescopes

Anton Koekemoer, koekemoer@stsci.edu, for the MAST team

The Barbara A. Mikulski Archive for Space Telescopes (MAST) is one of NASA's premier astronomy data centers, along with the High Energy Astrophysics Science Archive Research Center (HEASARC) and the NASA/IPAC Infrared Science Archive (IRSA). MAST is the primary archive repository for data from several large, active space missions (*Hubble*, *Kepler*, *XMM-OM* and *Swift*-UVOT), legacy data from past missions (*GALEX*, *FUSE*, *IUE*, *EUVE*, and others), planned data from future missions, such as *James Webb Space Telescope*, and all-sky surveys such as VLA-FIRST, GSC and DSS.

MAST supports the scientific research carried out by the astronomical community by facilitating access to its collections, offering expert user support and software for calibration and analysis, and providing value-added scientific data products. These include high-level science products (HLSPs) such as mosaics, catalogs, and spectra delivered to MAST by science teams, as well as enhanced products accessible via the *Hubble* Legacy Archive (HLA) and the *Hubble* Source Catalog. Current MAST news and updates are posted on our main archive website (<http://archive.stsci.edu>) and on social media, including Facebook (<https://www.facebook.com/MASTArchive>) and Twitter (https://twitter.com/MAST_News). MAST also makes available HLSPs from Treasury, Archival Legacy, and Large programs (see <http://archive.stsci.edu/hst/tall.html>).

Hubble Frontier Fields high-level science products available in MAST

The *Hubble* Frontier Fields program (P.I.: J. Lotz/M. Mountain) has completed observations of the first two targets of the program, Abell 2744 and MACS J0416.1-2403, reaching a total of 140 orbits of exposure time on each target cluster field, as well as its associated parallel field. The observations for each target were divided into two epochs, in order to obtain data on both the cluster field and its associated parallel field using the Advanced Camera for Surveys (ACS) in the F435W, F606W and F814W filters, as well as the Wide Field Camera 3 (WFC3) in the F105W, F125W, F140W and F160W filters. Throughout the course of each epoch, the *Hubble* Frontier Fields Team at the Institute has produced and delivered cumulative-depth v0.5 mosaics, as well as full-depth v1.0 mosaics at the end of each epoch, including all archival data to produce the deepest current images of these fields. The Frontier Fields Team has also carried out extensive scientific value-added processing beyond standard calibration, to address instrumental effects such as bias de-stripping, dark current residuals, persistence, flat-fielding uncertainties, time-variable sky background, and a variety of other calibration effects, all of which are described in more detail in the documentation that is provided together with the mosaics for each release.

Observations of the third and fourth targets in the Frontier Fields program, namely MACSJ0717.5+3745 and MACSJ1149.5+2223, are currently in progress, and the Frontier Fields Team has already carried out several mosaic release products for these fields as well. To date, the team has produced and released a total of 25 datasets for the entire Frontier Fields program (including cumulative-depth v0.5 releases as well as full-depth v1.0 releases). As of December 2014, a total of 6.9 TB of these products had been downloaded by 1591 separate IP addresses. Over 60 refereed papers have been published using these data, with results covering topics such as high-redshift galaxies and supernovae, dark matter physics, and lensing analysis (see the talks presented at the recent Yale Frontier Fields Workshop http://www.astro.yale.edu/yale_frontier_workshop/ for the latest results). In addition, MAST provides access to lensing models of these clusters that have been contributed by teams in the community (led by M. Bradač, J.-P. Kneib, P. Natarajan, J. Merten, A. Zitrin, K. Sharon, and L. Williams). All these products may be accessed directly from the MAST Frontier Fields website (<http://archive.stsci.edu/prepds/frontier/>).



Figure 1: Complete, full-depth mosaics of the first two Frontier Fields clusters and their associated parallel fields, each observed to its full depth of 140 orbits with ACS in the F435W, F606W, and F814W filters, and WFC3/IR in the F105W, F125W, F140W, F160W (image credits: J. Lotz, M. Mountain, A. Koekemoer, and the *Hubble* Frontier Fields Team). *Top row:* Abell 2744 main cluster field (*left*) and parallel field (*right*). *Bottom row:* MACS J0416.1-2403 main cluster field (*left*) and parallel field (*right*).

The MAST Data Discovery Portal

We encourage all users to try the latest version of MAST Data Discovery Portal (accessible at <http://mast.stsci.edu/explore>) which enables graphical browsing and queries of images, catalogs and other data from all the missions currently available through MAST, as well as direct queries of other datasets available via the Virtual Observatory. The latest features include support for overlaying catalogs, interactive spectral previews, and cross-matching data on a given target using different instruments and telescopes.

GALEX unique source catalogs

Two source catalogs for *GALEX* are now available from MAST, namely GCAT (a project led by M. Seibert) and BCS (Bianchi, Conti, & Shiao 2014). The GCAT is based on All-Sky Imaging Survey (AIS) tiles and Medium-Sky Imaging Survey (MIS) observations up to and including the GR6 release, as well as GR7 data in the *Kepler* area. It is a near-ultraviolet (NUV) catalog, containing objects that are detected with a signal-to-noise ratio greater than three, and represents the “best,” or deepest, observations for a given source. The BCS catalog uses both the AIS and MIS datasets up to GR7, and requires at least one observation when the far-ultraviolet (FUV) and NUV detectors are on. These catalogs are optimal for cross-matching *GALEX* UV fluxes with data in other bands, or for Galactic and extragalactic population studies. All the catalogs, together with interactive interfaces to query them, are available at the following two webpages for the GCAT and BCS catalogs, respectively: <http://archive.stsci.edu/prepds/bcscat/> or <http://archive.stsci.edu/prepds/gcat/>.

GALEX UV emission maps

Jayant Murthy has created maps of the diffuse ultraviolet (UV) radiation as observed by *GALEX*, in both far-ultraviolet (FUV) and near-ultraviolet (NUV) bands, using the latest *GALEX* all-sky data release (GR6+GR7). Tables are provided of the diffuse radiation for each *GALEX* visit at a resolution of two arcminutes, organized by galactic latitude. In addition to the diffuse background fluxes in NUV and FUV, estimates are also provided of the geocoronal and zodiacal foreground emissions for each binned pixel. Aitoff projections of both the FUV and NUV diffuse radiation (and its

variance), along with a 100-micron emission map based on the Schlegel et al. (1998) dust maps, are provided in FITS format. Finally, a table of *GALEX* spacecraft telemetry used to generate these data products is included. Full details are available at: <http://archive.stsci.edu/prepds/uv-bkgd/>.

White dwarf ultraviolet line list

A team led by Simon Preval has created one of the most complete UV linelists of a white dwarf. Co-adding over 150 spectra from both *HST*/STIS and *FUSE*, the team was able to identify nearly 950 absorption lines with equivalent widths as small as a few mÅ. They were able to identify every observed feature in the coadded *FUSE* spectrum, and nearly every feature in the coadded STIS spectrum. In addition to line identification, the team was able to measure abundances for nine elements (C, N, O, Al, Si, P, S, Fe, Ni). For full details of the data reduction, line identification, and analysis, we refer the reader to the original paper (Preval et al. 2013). At MAST, we provide the complete linelist, as well as the spectra (individual and coadded versions), as a HLSP. The linelist is provided as an ASCII text table, while the spectra are in FITS format, as explained in the Data Format section. Links to an interactive plotting tool for users to explore these high-quality white-dwarf spectra are provided in the Atlas table below. Note that the *HST*/STIS spectra did not have additional dispersion corrections applied as suggested by Ayres (2010), but a future release may include versions of the spectra with these corrections. The line lists, along with the coadded spectra and the individual spectra, are all available at: <http://archive.stsci.edu/prepds/wd-linelist/>.

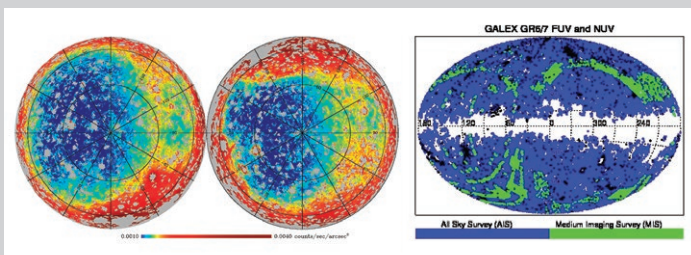


Figure 2: Left: Coverage map of the GCAT catalog (Siebert et al.). Right: Coverage map of the BCS catalog (Bianchi, Conti & Shiao 2014).

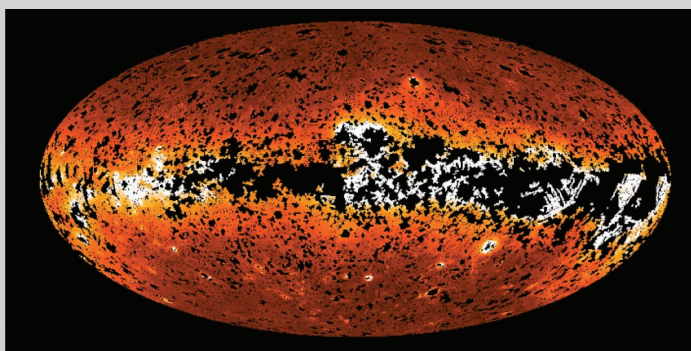


Figure 3: The all-sky map of diffuse radiation observed by *GALEX* in the NUV band.

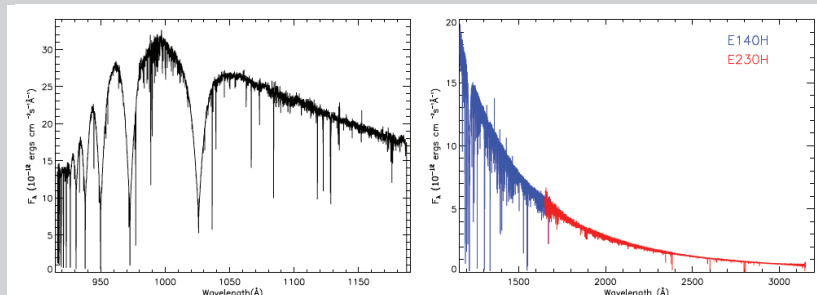


Figure 4: The full combined spectra of the white dwarf G191-B2B (Preval et al.), produced by co-adding over 150 separate spectra that had been obtained using STIS and *FUSE*.

Hubble moving-target reprocessed images

A project led by M. Mutchler is producing reprocessed images for moving targets in the *Hubble* archive, aimed at overcoming many of the challenges that are specific to moving-target observations with *Hubble*. This project includes ACS, WFC2, and WFC3 images, all reprocessed with different cosmic ray rejection parameters, and using drizzle parameters that are optimized for moving targets. The interface provides access to all the image products, as well as predicted ephemerides of known moving-targets within an image.

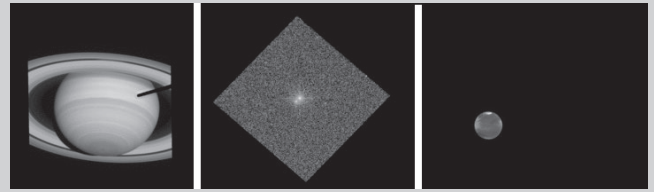


Figure 5: Examples of reprocessed moving target images available from the *Hubble* Moving Target Project (Mutchler et al., in prep.)

Hubble Legacy Archive (HLA)

The HLA has made available Data Release 8, which includes improved WFC3 image data produced using DRIZZLEPAC, as well as improved WFC3 source lists which are available for more observations and are deeper than previous versions. All WFC3 non-GRISM data that were public as of June 1, 2014 have also now been processed, and the number of WFC3 images and catalogs is larger by a factor of 2.6 compared with the previous release. The user interface has also been enhanced for visits that have more than three filters available, so that the color image entries provide access to all the filters in the interactive display. Finally, several aspects of the source list overlays have been improved in the interactive displays, including improvements to overlaying objects from the *Hubble* Source Catalog (HSC). For further details, please see the HLA page (<http://hla.stsci.edu/>), where updates continue to be posted as they become available.

Kepler updates

The ingest of Data Release 24 has begun. This delivery contains Long-cadence Lightcurves (LLC) and target pixel files (TPF). In addition, the *Kepler* Objects of Interest (KOI) table as provided by NASA Exoplanet Science Institute (NExSci) includes about 40 new entries, with all entries now having assigned dispositions. New columns were added for insolation flux, fitted stellar density, planetary fit type, TCE planet number and TCE delivery name. For further details, please see the relevant MAST webpages for *Kepler* (<http://archive.stsci.edu/kepler/>) and the proposed K2 mission (<http://archive.stsci.edu/k2/>).

As always, please feel free to contact the MAST help desk (archive@stsci.edu) with questions, or contact us through Facebook ([MASTArchive](#)) or Twitter ([@MAST_News](#)) to provide suggestions on how we can improve our sites and services.

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The Search for Life Is Picking Up Speed!

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Recently, the search for extraterrestrial life has started to gain significant momentum. NASA has just announced, for instance, that it is setting aside \$25 million to develop the scientific instruments needed for a mission to Europa (Figure 1). This is the ice-covered moon of Jupiter that could harbor life in the ocean underneath its icy exterior. Finding any form of life on a solar system body other than Earth—be it Mars, or one of the satellites Europa, Enceladus, or Titan—would indeed be very exciting. The true revolution, however, will ensue once we find *extrasolar life*—life on a planet orbiting another star. The main reason that makes extrasolar life the much bigger prize is very simple. If extraterrestrial life is found within the solar system, unless it is absolutely clear that it has arisen independent of our lineage, there will always be the possibility that life on Earth and this newly found life had the same origin. The discovery of life in a planetary system around another star, on the other hand, will immediately imply that life is not exceedingly rare, with all the extraordinary biological and cultural implications.

Several factors have combined to advance the search for life to the level of a high-priority quest. First, the statistics of the discoveries by the *Kepler* space observatory have made it clear that there are billions of planets in our Galaxy that orbit their host stars in the so-called “habitable zone.” This is the range of distances that is neither too hot nor too cold, which allows for liquid water (thought to be a necessary

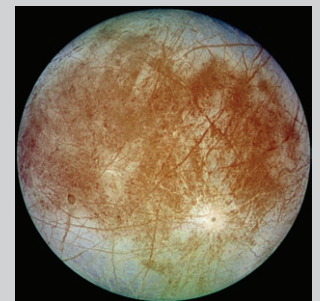


Figure 1. Jupiter's satellite. Image in the public domain.



Figure 2. The *Transiting Exoplanet Survey Satellite* (TESS). Credit: TESS team.

ingredient for life) to exist on the planet's surface. Second, the *Hubble* and *Spitzer* space telescopes have already demonstrated that they can (at least partially) determine the composition of the atmospheres of extrasolar planets (only gas giants so far). Third, and most important, the upcoming *Transiting Exoplanet Survey Satellite* (TESS; Figure 2), to be launched in 2017, and the *James Webb Space Telescope* (JWST; Figure 3), to be launched in 2018, could (at least in principle) discover biosignatures in the atmospheres of Earth-size planets orbiting small (M-dwarf) stars. To constitute an unambiguous detection of life would probably require a combination of potential biosignatures, such as: inferred liquid water, oxygen and ozone, and an atmosphere that exhibits an extreme thermodynamic disequilibrium. To be sure, the chances that TESS and JWST will actually find life are small, but definitely not zero.

The key point is that with the currently upcoming and the proposed telescopes (such as a 16-meter optical-ultraviolet space telescope with the acronym ATLAST), it appears that finding extrasolar life is, for the first time in human history, within reach. A similar optimism seems to be associated with the search for extraterrestrial intelligent life (SETI).

In fact, I would venture to state that if extrasolar life is *not* found within the next thirty years, I would be amazed. Ultimately, what makes the search for extra-solar life one of the most (if not *the* most) fascinating scientific endeavors, is the fact that you don't have to be a scientist to realize that its discovery would dwarf by comparison even the Copernican and Darwinian revolutions combined!

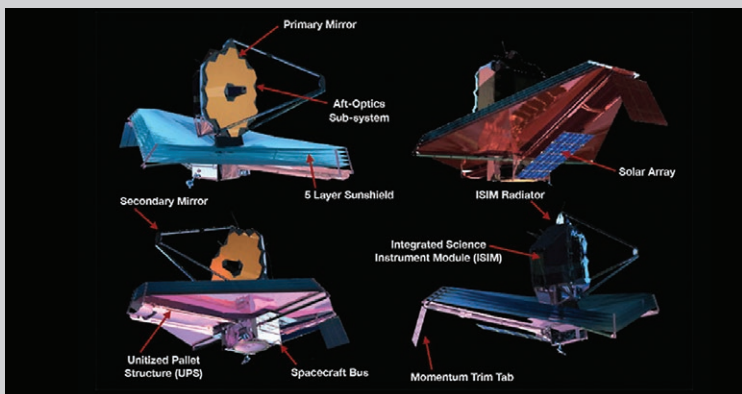


Figure 3. The *James Webb Space Telescope* (JWST). Image in the public domain.

Exploiting Nature's Telescopes

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Priyamvada Natarajan was the 2011–2013 Caroline Herschel Distinguished Visitor at the Space Telescope Science Institute. She is Professor in the Departments of Astronomy and Physics at Yale University. (<http://www.astro.yale.edu/priya/>).

The discovery of the microscope and telescope transformed science in the 17th century and brought into view new realms that were otherwise inaccessible. Now the extension offered by cluster lenses—nature's own telescopes—enhances our reach of the night sky and offers a glimpse of distant galaxies that would never ever be visible to us, no matter how far our technology progresses. Clusters of galaxies, the most massive and recently assembled structures in the universe, are the perfect astrophysical laboratories to tackle many pressing and key problems in cosmology today (for details, see review by Kneib & Natarajan 2011).

Einstein's theory of general relativity predicts the bending of light rays by intervening mass distributions. Dark-matter-dominated clusters of galaxies are the perfect lenses that deflect light from distant background populations of some of the earliest galaxies that likely assembled soon after the Big Bang. How these first galaxies formed and evolved is, of course, one of the key open questions in galaxy formation. The nature of dark matter remains elusive as well, despite our growing knowledge of how dark matter is distributed spatially in the universe, and that it aggregates in the most massive structures—clusters—clues to its nature are sparse at present.

Lensing reconstructions of the dark-matter distribution in clusters offers powerful checks on the validity of the currently accepted paradigm of a universe dominated by cold dark matter. Precision tests of this theoretical framework are possible with high-resolution mass reconstructions of galaxy clusters. High

quality data can illuminate dark-matter properties, and cosmography with cluster lenses can provide strong constraints on cosmological parameters like dark energy. In addition to learning about clusters and their assembly history, gravitational lensing studies also offer the unique opportunity to study the population of highly magnified background sources with unprecedented detail. Therefore, cluster lensing offers an efficient way forward to pin down the sources that caused re-ionization of the early universe. However, to fully exploit the unique and potent capabilities of clusters, extremely high-resolution, deep images are needed, like those produced by *Hubble*'s Advanced Camera for Surveys (ACS).

A new opportunity to acquire just this kind of exquisite data has become possible with the **Frontier Fields Initiative**, undertaken with broad community input as a large *Hubble* survey beginning in Cycle 21. The observational strategy of the Frontier Fields program consists of ~140 orbits devoted per cluster/blank-field pair region, achieving AB \approx 28.7–29 mag optical (ACS) and NIR (Wide Field Camera 3; WFC3) imaging with 560 orbits in Cycles 21/22. The six cluster candidates, all of intermediate redshift because it provides the optimal lensing geometry for distant sources, are Abell 2744 ($z = 0.308$); MACSJ0416 ($z = 0.396$); MACSJ0717 ($z = 0.545$); NACSJ1149 ($z = 0.543$); AbellS1063 ($z = 0.348$) and Abell 370 ($z = 0.375$). Propelled by the success of the earlier deep-field initiatives, namely *Hubble* Deep Field (pioneered by then-director Bob Williams in 1995) and the Ultra-Deep Field (in 2003), a *Hubble* Deep Fields Initiative Committee was set up by Institute director Matt Mountain in 2012 to recommend new initiatives with the *Hubble* that could attack fundamental problems in astrophysics. Weighing in advice from the astronomical community and deliberating on the set of critical science questions that could greatly advance our knowledge of early galaxy formation, the Committee recommended a program of six deep fields centered on strong lensing galaxy clusters in parallel with six deep flanking "blank fields." This recommendation was enthusiastically accepted, and the **Frontier Fields** program was developed with Jennifer Lotz and Matt Mountain as Co-PIs. *Spitzer* has also committed to supporting this effort and is providing commensurate data. A total of 50 hours of integration with *Spitzer*'s IRAC instrument are being spent in each of the 3.6 and 4.5 micron channels (<http://ssc.spitzer.caltech.edu/warmmission/scheduling/approvedprograms/ddt/frontier/>).

The science goals of these new deep fields are: (1) to understand the detailed distribution of dark matter in clusters and compare with theoretical models; (2) to use the magnifying power of cluster lenses to unravel currently inaccessible galaxy populations at $z = 5$ –10 that are intrinsically 10–50 times fainter than any presently known, consolidating our current understanding of the stellar mass assembly of sub-L galaxies at the highest redshifts; (3) to provide the first statistically meaningful morphological characterization of star-forming galaxies at $z > 5$, and to find $z > 8$ galaxies stretched out enough by cluster lensing to discern internal structure and/or magnified sufficiently for spectroscopic follow-up.

The ongoing *Spitzer* Frontier Fields program focuses on complementary science goals to (a) better understand the stellar masses and star-formation histories of sub-L galaxies at the highest redshifts, (b) provide the first statistically meaningful characterization of the stellar populations in star-forming galaxies at $z > 5$, and (c) find high redshift $z > 8$ galaxies magnified sufficiently by cluster lensing to enable spectroscopic follow-up.

Pre-FF submitted lens models of Abell 2744

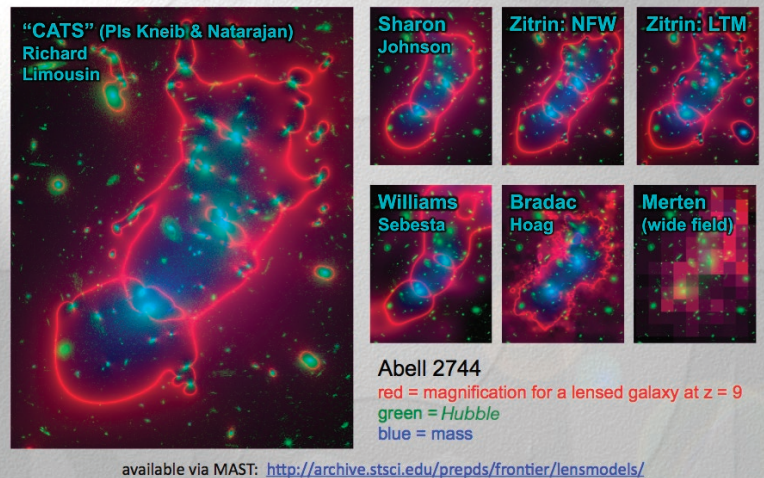


Figure 1: Preliminary magnification maps for one the FF clusters, Abell 2744, provided by selected map-making groups prior to the new data. These maps were constructed with existing *Hubble* data (prior to the *Hubble* FF program). Similar magnification maps computed for background sources at $z = 9$ for all 6 frontier field targets are available at <http://archive.stsci.edu/prepds/frontier/lensmodels/>. The scale of the map is the field of view of the WFC3-IR detector [approx. 2 arcmin \times 2 arcmin].



Figure 2: The public *Hubble* FF data for the cluster Abell 2744: ACS Optical (left panel) and the WFC3/IR (right panel).

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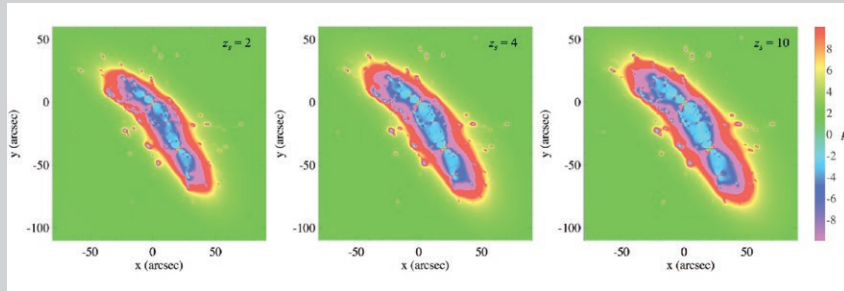


Figure 3: The magnification maps of the FF cluster MACS0416 for sources at $z = 2$, 4 and 10 from the Grillo et al. (2014) best-fit model that comprises of 2 large-scale PIEMD models for the smooth component of the dark-matter distribution and 175 smaller galaxy-scale halos.

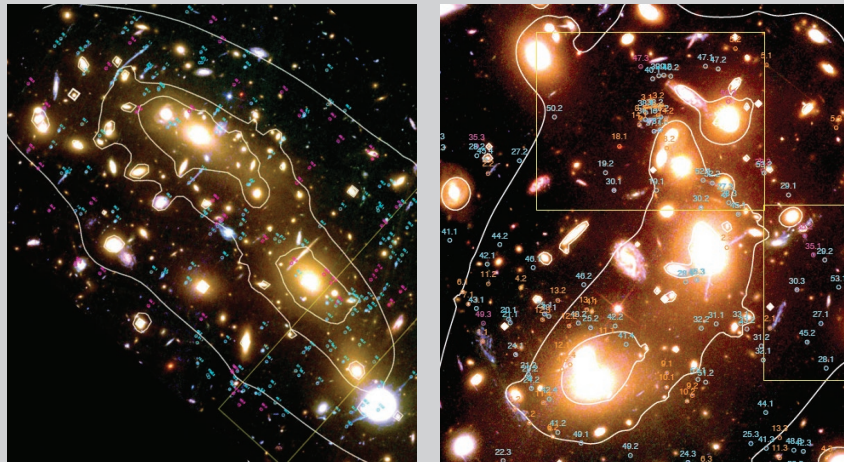


Figure 4: The reconstructed mass distribution in Abell 2744 (*right panel*) and MACS0416 (*left panel*) obtained with strong lensing data from the *Hubble* FF program (published by Jauzac et al. 2014a,b). These particular mass models of Abell 2744 utilize 159 images from 51 sets of multiples and 194 multiply imaged sources in MACS0416. These mass maps have unprecedented small statistical errors compared to models generated from earlier shallower *Hubble* data.

Details of the observational program can be found at <http://www.stsci.edu/hst/campaigns/frontier-fields/HST-Survey>. A timely workshop titled “Cluster Lensing: Peering into the past, planning for the future” was convened in 2013, followed by a recent workshop highlighting first science results “Yale Frontier Fields Workshop: Shedding Light on the Dark Ages and Dark Matter” held in New Haven in November 2014.

Since magnification maps of these lenses are crucial to extracting science from the public data, Jennifer Lotz, Ken Sembach, and Neill Reid at the Institute selected five groups to provide preliminary magnification maps prior to the start of new observations. These maps provided by independent groups are available publicly for the astronomical community at the Mikulski Archive for Space Telescopes (MAST) archive <http://www.stsci.edu/hst/campaigns/frontier-fields/>.

In addition, an exercise to calibrate the reconstruction methodology is underway. It compares the models and maps produced for a simulated cluster by different groups deploying independent mass modeling techniques. The author, Dan Coe, and Massimo Meneghetti have recently finished Phase II of this exercise and upon completion of the next (final) stage, the results of comparing maps submitted by various groups for a set of simulated clusters will be published in the refereed literature and also be made available online.

The first science results from Abell 2744 and MACS0717.5+3745, the two FF clusters with completed observations, are extremely exciting. Below are a few glimpses of some of these new findings from characterizing the mass distribution of the lenses and exploiting them as telescopes to detect high-redshift galaxies and supernovae. More details can be found on the Yale Workshop site where PDF files of all talks are available at the following URL: http://www.astro.yale.edu/yale_frontier_workshop/schedule.php

Characterizing the cluster lens

Several groups have published dark-matter maps for the first two FF clusters, Abell 2744 and MACS0416. The magnification maps from one group (Grillo et al. 2014) are shown in Figure 2, and the combined strong + weak lensing reconstruction for Abell 2744 (Jauzac et al. 2014b) is shown in Figure 4. As expected, these two massive lensing clusters have complex geometries with merging sub-clusters, thus requiring multiple large-scale components and numerous smaller galaxy-scale sub-halos to model their mass distributions. In contrast to previous *Hubble* data, the quantum leap in the number of multiple images that are now available to constrain the models is unprecedented. In the case of Abell 2744, with the FF data we now have ~250 multiple images that are used in the reconstructions, thereby bringing down the statistical errors to the few percent level compared to earlier work. With *Hubble* FF data, it turns out that modeling techniques require refinement and honing, where previously with sparser data the opposite was true—the data was insufficient to yield unique models. We will be able to provide robust quantitative estimates for systematic errors as soon as the model comparison exercise has concluded.

Exploiting nature's telescopes

As an important and unexpected bonus, the FF clusters to date have yielded a total of 25 SNe out to $z \sim 1.5$ with two confirmed background supernovae, one that is singly imaged and magnified, and the other an extremely rare quadruply imaged Einstein cross at $z = 1.491$ lensed by an early-type galaxy cluster member boosted by the overall cluster in MACS1149 (shown in Figure 5). This unique system is likely to provide strong constraints on the mass of the cluster galaxy as well as the cluster (Kelly et al. 2014). It will also provide an important test for the lens modelers. The predicted lens model magnifications for one of the singly imaged, spectroscopically confirmed Type Ia supernova detected by Rodney et al. (2014)—HFF14Tom at $z = 1.33$ in Abell 2744—are systematically and significantly higher than estimated from the fact that it is a standard candle. At a distance at 40 arcseconds from the cluster center at the edge of the strong lensing region, this suggests (as suspected) that all lens models contain systematic biases that at present are not well quantified, and uncertainties remain under-estimated.

Another candidate, the supernova HFFJan14, has now been confirmed to be a Type Ia (Foley et al. 2014). A spectrum obtained from Gemini-North in the wavelength range 460–965 nm confirms this spectral classification. This SN, with a measured redshift of $z = 0.305$, however, lies in the foreground of the cluster Abell 370 consistent with photometric redshift estimates. This one, therefore, does not provide any constraints on the mass modeling. Another strongly lensed transient object consisting of two images—originally believed to be an SNe—appears to not be so. This peculiar object, HFF14Spo, appears in the optical, rises in luminosity by ~1 magnitude, and then fades in less than 3 rest-frame days. The nature of this object is, as yet, undetermined. On a diagnostic plot of the peak luminosity versus characteristic time-scale in days, it appears to be similar to the “intermediate” luminosity SN-like objects detected in a recent PTF survey by Kasliwal et al. (2011). It is unclear if this kind of new optical transient, including HFF14Spo, are standard candles.

One of the primary science drivers for the *Hubble* FFs was the ability of these massive cluster lenses to bring into view faint, high-redshift, $z > 6$ populations of galaxies to determine the properties of the earliest structures to form and their role in re-ionization of the universe. Using the preliminary magnification maps (with pre-HFF data) made available to the astronomical community, as well as the maps made with *Hubble* FF data, several groups have made independent determinations of the slopes and normalizations of the luminosity function (LF) of sources at $z = 6, 7, 8$, and 9. Current determinations from the *Hubble* FF data are broadly in agreement with prior estimates from the deep blank fields. There is, however, considerable dispersion amongst groups in the determined value of the faint end slope of the LF at $z = 8$ and 9 (Atek et al. 2014; Oesch et al. 2014; McLeod et al. 2014; Laporte et al. 2014; Vanzella et al. 2014). Crucial to this determination is the estimation of completeness where the uncertainties in the magnification maps come into play. The variation in the reported values for the faint-end slope of the LF likely arises from differences in how the completeness is assessed and the reliable identification of high- z galaxies given the uncertainties in their photometric redshifts.

With updated magnification maps from the full FF data, the various LFs should come into better agreement. Analyzing drop-out galaxies from the full FF data of Abell 2744 and the flanking fields Ishigaki et al. (2014) report tension between the determined UV star-formation rate density from faint end LF slope and the measured large Thomson scattering depth inferred from CMB experiments. In addition, grism spectra of the *Hubble* FF sources from the GLASS project have started to reveal emission lines in $z > 6$ lensed galaxies (Schmidt et al. 2014). Another exciting find has been the reported discovery of a candidate lensed $z \sim 10$ galaxy using the photometric drop-out technique, potentially yielding one of the least luminous galaxies to be detected at this redshift if its spectroscopic redshift is confirmed (for details see Zheng et al. 2014 and Zitrin et al. 2014). Vigorous multi-wavelength follow-up is also underway.

Cluster modeling comparison exercise

In order to quantify the systematic errors incurred in cluster mass modeling, we have been conducting a comparison of independent methods employed by various groups. Lensed images from a simulated

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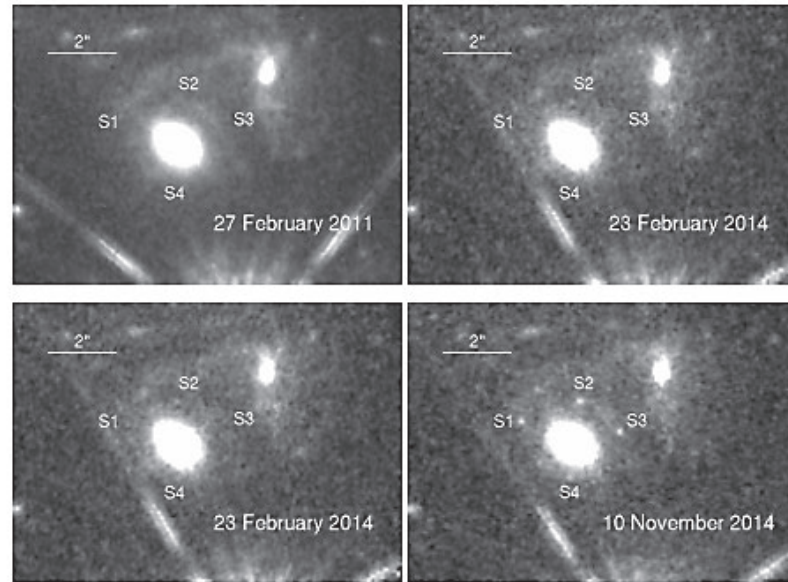


Figure 5: The newly discovered, rare quadruply imaged Einstein cross—a supernova in a background spiral galaxy arm lensed by a cluster elliptical in MACS1149. In honor of one of the pioneers of lensing, Sjur Refsdal, this SN bears the name Refsdal. Images of the lensing system are from archival WFC3-IR observations in the F140W filter. All exposures obtained prior to 3 November 2014 show no evidence for variability at any of the positions associated with SN Refsdal.

cluster were provided to the participant groups and sets of well-defined metrics were devised for comparing models to the true values. Starting with a simple cluster in Phase I of the exercise, we have just completed Phase II that required the reconstruction of a more complex cluster mass distribution. We have now provided the participating groups' analysis of the performance of their codes *viz-à-viz* the true maps for the first two simulated clusters in order to help them refine their methods. We intend to conclude this effort by providing the modelers with one more simulated cluster prior to publishing the results of this exercise in 2015. The results of this entire exercise will be made available to the community.

Even the first, early results from the *Hubble* Frontier Fields are revolutionizing our understanding of clusters and the distant objects that they serendipitously bring into view. By the time the FF program concludes we might well be forced to re-conceptualize clusters and perhaps all dark-matter concentrations in the universe!

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Debris Disks and the Search for Life

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Planetesimals are the building blocks of planets. We can trace them by the dust they produce by collisions and sublimation, which forms a debris disk around the star. This "zodiacal" dust has a variety of scientific connections and implications. It also poses an observational issue for direct planet detection, due to the background noise and confusion it may introduce (Brown 2015; Stark et al. 2014). While zodiacal emission is an issue for planet-finding at visible and near-infrared wavelengths, the latest information comes from far-infrared observations of dust in the outer reaches of planetary systems. The high frequency of planetesimals around solar-type stars has also sparked renewed interest in lithopanspermia—the distribution of life between planets and even planetary systems.

Planetesimals

The evidence for planetesimals comes from infrared emission in excess of that expected from stellar photospheres. This emission is thought to arise from circumstellar dust. Because the lifetime of the dust grains is < 1 Myr, which is much shorter than the age of the star (> 10 Myr), we infer that the dust cannot be primordial. It must be steadily or stochastically produced by collisions, disruptions, and/or sublimation of larger bodies—planetesimals (for a review, see e.g., Wyatt 2008; Moro-Martín 2013).

Mid- and far-infrared observations with *Spitzer* (3.6–160 μ m) and *Herschel* (70–500 μ m) indicate that at least 10–25% of stars of age 0.01–10 Gyr harbor planetesimal disks with radial extent in the range 10s–100s AU. This frequency is a lower limit because the surveys are limited by sensitivity.

We find evidence for planetesimals around A- to M-type stars, and also around the progenitors of white dwarfs (Jura 2007). These stars span orders of magnitude in stellar luminosity, implying that planetesimal formation is a robust process and can take place under a wide range of conditions. This conclusion is consistent with studies that find a correlation between stellar metallicity and the occurrence of massive planets (Santos et al. 2004; Fisher & Valenti 2005). There is, however, no correlation between stellar metallicity and the presence of debris disks (Greaves et al. 2006; Bryden et al. 2006; and Moro-Martín et al. 2015, based on data from the James Clerk Maxwell Telescope, *Spitzer*, and *Herschel* respectively).

Detailed analysis of spectra of infrared excess obtained with *Spitzer* indicates that cold dust disks are common around solar-type (FGK) stars, with a characteristic dust temperature 60–180 K, and with inner

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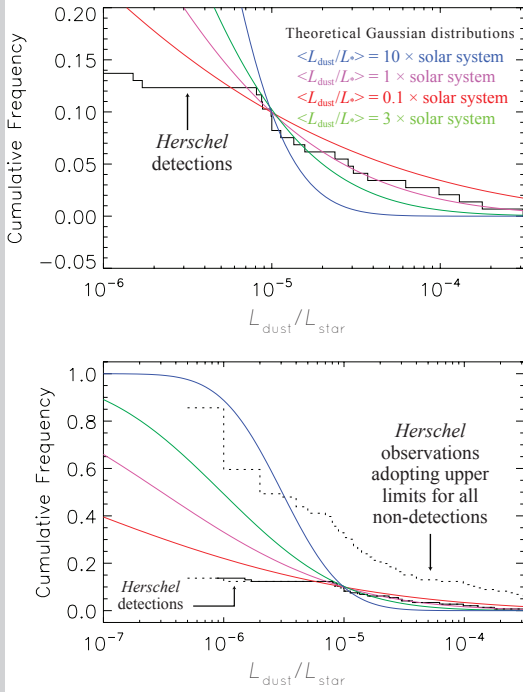


Figure 1: Cumulative frequency of the fractional luminosity observed by (solid line), compared to theoretical distributions that assume a Gaussian distribution in logarithmic scale, centered at $10\times$, $3\times$, $1\times$ and $0.1\times$ the solar-system value (colored lines). *Top*: showing only the detected range; there are only three targets with fractional luminosities below 8×10^{-6} , compromising the fit to the data in that low range, because of small-number statistics. *Bottom*: the two dotted lines assume a pessimistic and an optimistic case, respectively, where the adopted fractional luminosities for the targets without excess detections are taken to be zero (pessimistic) or its corresponding upper limit (optimistic).

disk cavities 10–40 AU in radius (Carpenter et al. 2009). These dust disks are in a regime where the dynamics of the dust particles are mostly controlled by collisions, and therefore the dust traces the location of the planetesimals. These results indicate that most of the planetesimals inferred to exist around mature, solar-type stars are analogous to the Kuiper Belt, in the sense that they have large inner cavities. The inner radius of the Kuiper Belt is ~ 35 AU.

The sun also harbors a debris disk, produced by the asteroids, comets, and Kuiper Belt objects (Jewitt et al. 2009), with a production rate of dust that has changed significantly with time, having been higher in the past, when the solar system was less than ~ 700 Myr old. At those earlier times, the asteroid and Kuiper belts were more densely populated; they were depleted by planetary migration. Today, the solar system's debris disk is fainter than the faintest extrasolar debris disks we can observe with *Herschel*, with a $3\text{-}\sigma$ detection limit at 10–20 times the level of dust in the current Kuiper Belt (Eiroa et al. 2013; Matthews et al., in preparation).

Fractional luminosity and exozodi

Fractional luminosity is a variable commonly used to characterize debris-disk emission. It allows comparison of disks observed at different wavelengths, and it is not strongly model-dependent, as long as the wavelength coverage is good—as is the case for the stars in our sample. Fractional luminosity can also help place *Herschel* observations of debris in the context of the solar system's debris disk.

Figure 1 shows the cumulative frequency of the fractional luminosity of dust, $L_{\text{dust}}/L_{\star}$, from an unbiased sample of 204 solar-type stars observed with as part of the DEBRIS and DUNES surveys. The stars in this sample are located at distances <20 pc (to maximize survey completeness), with ages >1 Gyr (to avoid the effect of disk evolution), and with no binary companions within 100 AU, to minimize gravitational disruption. The debris-disk frequency within this unbiased sample is $0.14^{+0.03}_{-0.02}$ (Moro-Martín et al. 2015).

The blue, green, magenta, and red lines in Figure 1 are theoretical distributions that assume a Gaussian distribution of fractional luminosity in logarithmic scale, with mean values of 10, 3, 1 and 0.1 times the solar-system value, $L_{\text{dust}}/L_{\text{sun}} = 10^{-6.5}$, respectively. The $1\text{-}\sigma$ widths (dex) of the theoretical distributions are 0.4, 0.8, 1.18 and 2.0, respectively. We fixed the cumulative frequency of disks with $L_{\text{dust}}/L_{\star} = 10^{-5} > 10$ to 10%, which is the frequency observed in our sample. The Gaussian distribution centered on the solar-system value (magenta line) fits the data well, while one centered at ten times the solar-system debris disk (blue line) exceeds the most optimistic case, so it can be rejected.

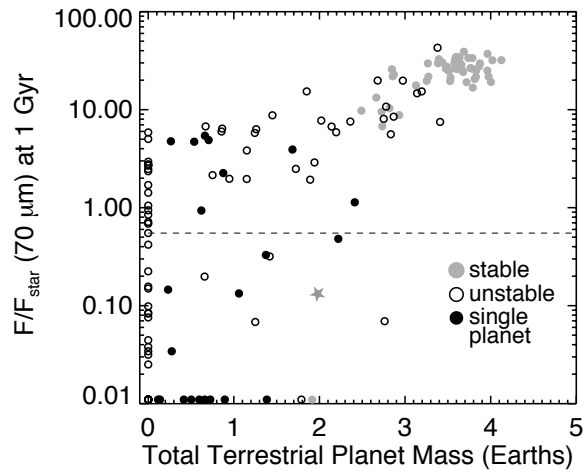
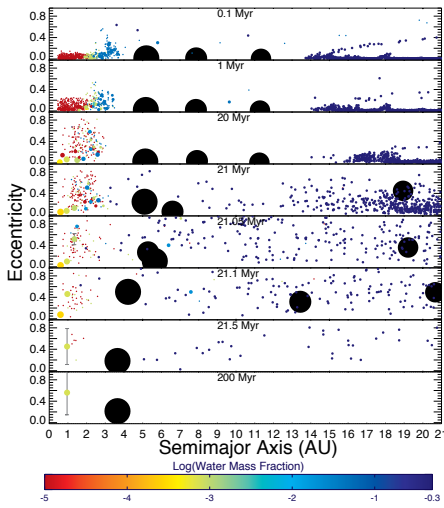


Figure 2: *Left*: Sample simulation showing that dynamically active, high-mass planets tend to destroy both the outer, dust-producing planetesimal belt and the building blocks of the terrestrial planets. *Right*: The dust-to-stellar flux ratio at $70\text{ }\mu\text{m}$ after 1 Gyr of dynamical and collisional evolution, plotted as a function of the total mass in terrestrial planets. Figures from Raymond et al. (2011).

Herschel detects emission from cold dust at 10s of AU from the stars with excess emission at 100 μm . The exozodiacal light—reflected starlight from dust at only a few AU—is a related phenomenon. We expect the fractional luminosity of the cold dust and the exozodiacal light to be correlated to some level because the dust in the region of the outer Kuiper Belt is likely one of the sources of the inner, zodiacal dust. This dust has been transported inward by Poynting-Robertson (PR) drag. We further expect the fractional luminosity and zodi to be proportional to the effective optical depths of the relevant dust, along their lines of sight. For debris disks, those optical depths are very small.

In the case of the solar system, the typical fractional luminosity (and optical depth) of zodiacal dust is $\sim 10^{-8}$ – 10^{-7} in the inner system (Dermott et al. 2002) and $10^{-6.5}$ in the outer system. In the case of other planetary systems, if the outer belt were to be the only source of exozodiacal dust—and assuming steady state and dust dynamics controlled by PR drag—one would expect

$$\text{exozodi} \approx \text{zodi} \times (L_{\text{dust}}/L_{\text{star}})/(L_{\text{dust}}/L_{\text{sun}}).$$

Under this assumption, our observations of fractional luminosity, with $L_{\text{dust}}/L_{\text{star}} < 10 \times L_{\text{dust}}/L_{\text{sun}}$, are good news for exoplanets, because exozodiacal light at the level of 10 zodis would not measurably reduce the expected performance of a 16m class, *ATLAST*-type telescope.

Ruling out a distribution of fractional luminosities centered at $10\times$ the solar-system level would mean good prospects for finding a large number of debris-disk systems with zodi emission low enough to be appropriate targets for terrestrial-planet searches. This is because, for planetary systems with dust at the solar-system level, PR drag dominates the dust dynamics, and causes the dust to drift inwards to the region where terrestrial planets are expected to occur.

The outer belt is not the only source of exozodiacal dust, however. Comets and asteroids located closer to the star are also sources of dust that can contribute to the zodi emission. For those sources, the long-wavelength observations do not provide constraints. Nevertheless, lower emission from Kuiper Belt-type dust likely implies less populated outer belts, which could reduce cometary activity.

There is more to the story, however.

Even though the planetesimals detected by *Herschel* in the far infrared are located far from the terrestrial-planet region, their presence indicates an environment favorable to the growth and survival of terrestrial planets. The planetesimals indicate that the system has experienced a calm dynamical evolution, as opposed to an environment of dynamically active, high-mass planets. Such an environment would tend to destroy both the outer, dust-producing planetesimal belt and the planetesimals that might otherwise build the terrestrial planets.

Figure 2 shows the results from extensive dynamical simulations by Raymond et al. (2011, 2012), consisting of high-mass planets, embryos, and inner and outer belts of planetesimals. These simulations find that there is a strong correlation between the presence of cold dust in the outer planetary

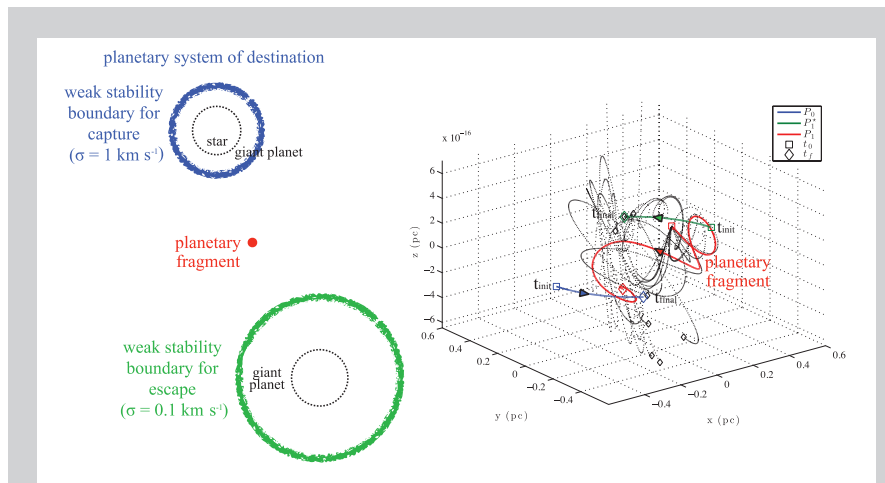


Figure 3: *Left:* Schematic representation of the weak-transfer process. It consists of a meteoroid weakly escaping from a planetary system and its subsequent weak capture by a neighboring planetary system in the stellar cluster. The meteoroid flies by the planet and weakly escapes the central star at approximately the location of the weak stability boundary created by the gravitational perturbation of the other $N-1$ stars in the cluster. The motion in this region is chaotic and lies in the transition between capture and escape. Then the neighboring cluster star weakly captures the meteoroid. *Right:* Few examples of the million Monte Carlo realizations carried out, showing the chaotic trajectory of a meteoroid that is successfully captured (in red), and others that are not captured (dotted black lines).

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system, and the presence of terrestrial planets in the inner region. Thus, a system with low levels of Kuiper-Belt dust emission might also imply a dynamical history not amicable to terrestrial planets. In this case, the solar system would be an outlier, with a low level of Kuiper-Belt dust but a high number of terrestrial planets. It would be of great interest to further explore this correlation by extending the Raymond et al. (2011, 2012) simulations to cover a wider range of initial conditions. This could shed light on the target selection for an *ATLAST*-type mission.

Lithopanspermia

Another link between debris and the search for life is the exchange of debris between young planetary systems, which may be more efficient than previously assumed. The phenomenon of dynamical transfer via chaotic, near-parabolic orbits makes lithopanspermia a viable hypothesis.

Having only one example of a habitable planet, there is little certainty regarding the frequency and timescale of abiogenesis once the conditions for life are met. Life could arise *in situ*, or it could be transferred from somewhere else. The exchange of meteoroids between the terrestrial planets in our solar system is a well-established phenomenon. The identification of a handful of meteorites on the moon and Mars has given rise to the concept of lithopanspermia: the transfer of life from one planet to another via the exchange of meteoroids. Nevertheless, the idea of lithopanspermia between different planetary systems—as opposed to between planets in the same system—has had a serious problem: extremely low transfer probabilities.

Until now.

Encouraged by the high frequency of planetesimals around solar-type stars, we have revisited the issue of lithopanspermia between planetary systems. We found that the transfer probabilities are greatly increased when considering quasi-parabolic, chaotic orbits (a.k.a. “weak transfer”; Belbruno et al. 2012). This mechanism, illustrated in Figure 3, could allow the exchange of large quantities of solid material between young planetary systems, when the stars were still embedded in the birth cluster. The efficiency of the exchange depends on the masses of the stars involved. For stellar masses between $0.5 M_{\text{Sun}}$ and $1 M_{\text{Sun}}$, we find that about 0.05–0.15% of the meteoroids that leave the first planetary system on nearly parabolic orbits are trapped by the second planetary system (its nearest neighbor in the cluster). This capture efficiency is a billion times larger than was found by previous studies using hyperbolic orbits to transfer meteoroids between the Sun and its nearest neighbor—after the stars have left the birth cluster (Melosh 2003). At that point, the relative velocities of the meteoroids are several km s^{-1} larger than the $0.1\text{--}0.3 \text{ km s}^{-1}$ that we considered to be characteristic of open clusters.

For lithopanspermia to be a hypothesis worth considering, the increased transfer probability is not enough; there needs to be a viable mechanism for weak transfer to take place after abiogenesis (see Figure 4), and the time for survival of microorganisms in deep space needs to be longer than the characteristic transfer time. In Belbruno et al. (2012), we explored the case of the Earth. We asked the question: could life on Earth have developed before the cluster dispersed? From the isotopic ratio of oxygen found in zircons, there are indications that liquid water was present in the crust of the Earth when the solar system was as young as 164 or 288 Myr, depending on the study, which indicates

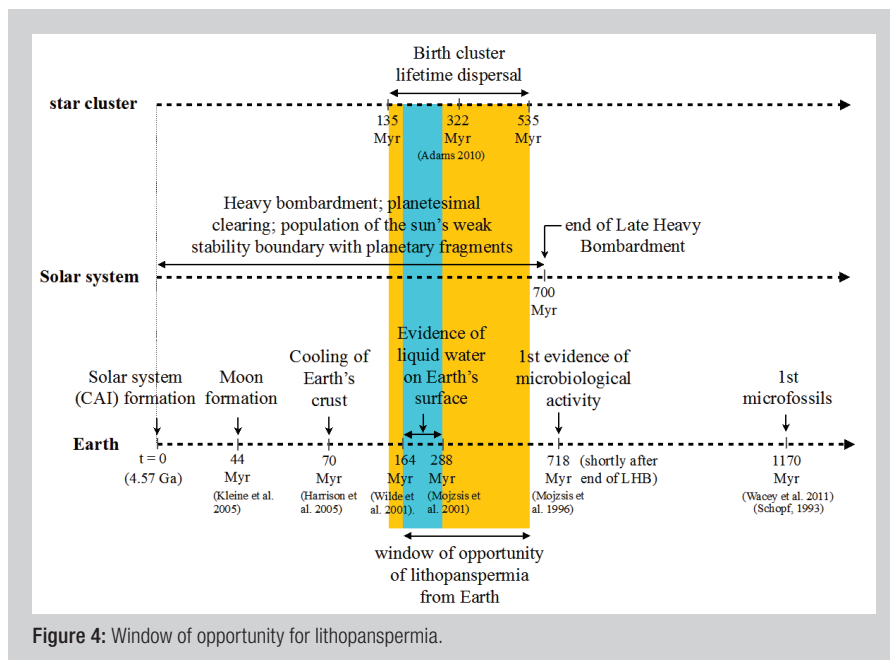


Figure 4: Window of opportunity for lithopanspermia.

that habitable conditions might have been present early on. Other studies show that the isotopic ratio of carbon in old sedimentary rocks indicates evidence of biological activity when the solar system was only 718 Myr. If this age estimate is correct, it means that life may have been present very shortly after the end of the era of the “late heavy bombardment.”

The timescales for abiogenesis are thought to range from 0.1–1 Myr for hydrothermal conditions at the deep sea, to 0.3–3 Myr for warm-puddle conditions in shallow water, to 1–10 Myr for subaeric conditions in the soil—all at least an order of magnitude less than the lifetime of the stellar cluster. If life arose on Earth shortly after liquid water was available on its crust, the window of opportunity for life-bearing rocks to be transferred to another planetary system in the cluster opens when liquid water was available (64–288 Myr), and ends by the cluster dispersal time (135–535 Myr; Adams 2010). Within this timeframe, heavy bombardment ejected large quantities of rocks from Earth. This bombardment period lasted from the end of the planet–accretion phase until the end of the late heavy bombardment 3.8 Gyr, when the solar system was approximately 770 Myr old (Tera et al. 1974; Mojzsis et al. 2001; Strom et al. 2005).

The bombardment is evidence that planetesimals were being cleared from the solar system several hundred million years after planet formation (Strom et al. 2005; Tsiganis et al. 2005; Chapman et al. 2007). This period of massive bombardment and planetesimal clearing completely encompassed the “window of opportunity” for the transfer of life-bearing rocks, providing a viable ejection mechanism for weak transfer to occur.

For lithopanspermia to work, the time for survival of microorganisms in deep space needs to be longer than the characteristic transfer timescale. Microorganisms can be sheltered from the hazards of outer space (ultraviolet light, x-rays and cosmic rays) if hidden below the surface of the rocks. Survival for millions of years cannot be tested with direct experiments (e.g., experiments testing the survival on the surface of the Moon lasted only a few years), but there are computer simulations that model the conditions in outer space for extended periods of time. A study based on these simulations (Valtonen et al. 2009) found that the survival times range from 12–15 Myr (for rocks with sizes of 0.00–0.03 m), 15–40 Myr (0.03–0.67 m), 40–70 Myr (0.67–1.00 m), 70–200 Myr (1.00–1.67 m), 200–300 Myr (1.67–2.00 m), 300–400 Myr (2.00–2.33 m), and 400–500 Myr (2.33–2.67 m). Given the timescales involved in the weak-transfer mechanisms, including the time it might take to land on a terrestrial planet, we find that microorganisms could survive the long interstellar journey hidden in meteoroids larger than about one meter.

It is therefore possible that life on Earth could have been transferred to other planetary systems when the Sun was still embedded in its stellar birth cluster. But could life on Earth have originated beyond the boundaries of our solar system? Our results indicate that, from the point of view of dynamical transport efficiency, life-bearing extrasolar planetesimals could have been delivered to the solar system via the weak-transfer mechanism if life had a sufficiently early start in other planetary systems, before the solar maternal cluster dispersed. An early microbial biosphere, if it existed, would likely have survived the Late Heavy Bombardment. Thus, both possibilities remain open: that life was “seeded” on Earth by extrasolar planetesimals, or that terrestrial life was transported to other star systems via dynamical transport of meteorites. Regarding the search for life beyond our solar system, this opens a new world of possibilities to dream about, given how many extra-solar planetary systems are out there and how tremendously diverse they are.

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Metals: Nature's Tracer Particles

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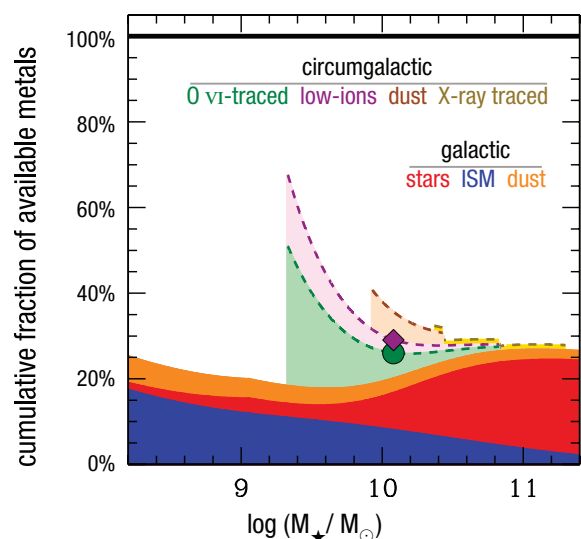


Figure 1: Cumulative fraction of metals in interstellar gas (blue), stars (red), interstellar dust (orange), the highly ionized circumgalactic medium (CGM; green), the low-ionization CGM (purple), circumgalactic dust (brown), and the hot X-ray-traced CGM (yellow) of star-forming galaxies. The points correspond to the median stellar mass of the COS-Halos galaxies. The total mass of metals a typical star-forming galaxy of a given stellar mass has produced in its lifetime corresponds to 100%. Though limited by a small sample of a few dozen galaxy-QSO pairs, in the CGM, COS-Halos does not find a dependence of the column density of gas (and thus the mass traced by that material) on the mass of the galaxy the gas is around; this constant mass is a much larger fraction of the total available metals in low-mass galaxies than in massive galaxies, hence the “wedge” shape seen here. Adapted from Peeples et al. (2014).

Nearly as soon as it was first realized that stars and supernovae are the formation sites for the heavy elements, metals have been used to trace the history of star formation, and of gas flowing out of and back into galaxies. The distribution of “nature’s tracer particles” in and around galaxies provides a snapshot of the cumulative history of these processes driving how galaxies evolve.

We have recently conducted an accounting of the metals in and around $z \sim 0$ star-forming galaxies (Peeples et al. 2014), comparing this empirical census to the budget of metals that galaxies have produced¹ in their lifetimes. We derive an empirical budget of available metals as possible by convolving empirically derived star-formation histories with recent estimates for supernova rates and nucleosynthetic yields; this allows us to account for the fact that bigger galaxies are also older, and thus have had a larger contribution from evolved stars and Type Ia supernovae. On the accounting side of the ledger, the metals contained in galaxies are found in stars and the interstellar medium (ISM). We take the mass of metals in stars to be the stellar metallicity times the stellar mass, while the mass of metals in interstellar gas is the gas-phase metallicity times the gas mass, and the mass of metals in interstellar dust is just the dust mass.²

A surprising result from this analysis is that star-forming galaxies contain a nearly constant ~20–25% of the metals they have produced in their lifetimes (Figure 1). In massive galaxies (stellar masses $>10^{10} M_{\odot}$), the bulk of these metals are trapped in stars, but in less massive galaxies, more metals can be found in the ISM. Strikingly, star-forming dwarf galaxies (stellar masses $<10^9 M_{\odot}$) have more metals in interstellar dust than they do in stars! That the “retained fraction” is so constant over ~3 decades in stellar mass goes against the intuitive expectation that massive galaxies’ deep potential wells cause them to be better at retaining (or re-accreting) supernova ejecta and other wind material. Most models of galaxy evolution assume or predict that low-mass galaxies are more efficient at driving galaxy winds, with an understanding that a steep scaling of the wind-driving efficiency is required in order to reproduce other galaxy population properties such

as the galaxy stellar-mass function. Such a steep scaling of outflow efficiency, however, is in tension with this new empirical result.

The challenge for models is greater than just retaining the observed fraction of metals. For example, galactic winds expel metals into the circumgalactic medium (CGM), which comprise the diffuse gaseous

¹We ignore metals that have only ever been in stellar remnants, as they are neither included in nucleosynthetic yields, nor easily accounted for.

²While our results are based primarily on scaling relations, extensive tests with cosmological hydrodynamic simulations have shown that such population averages accurately describe a “typical” galaxy.

halos extending hundreds of kiloparsecs around galaxies. By targeting UV-bright quasars whose sightlines pierce the CGM of foreground galaxies, we can systematically characterize the metallic (and baryonic) content of the CGM of low-redshift galaxies (Figure 2). The Cosmic Origins Spectrograph (COS), installed on *Hubble* in 2009, has greatly increased the number of such viable background sources, revolutionizing this field. The COS-Halos team (PI J. Tumlinson, GO 11598, 134 prime orbits) has used COS to measure the extent and kinematics of metals and baryons in neutral, low-ionization, and highly-ionized states out to 150 kpc around Milky Way-mass galaxies at $z \sim 0.25$. While it is relatively straightforward to calculate the mass traced by a single ionic species (surface density $\times \pi \times [150 \text{ kpc}]^2$), detailed ionization modeling is required to convert this to a *total* mass (Werk et al. 2014). These data uniquely constrain the fates of the $\sim 75\%$ of the metals that galaxies have produced, but are no longer in stars or the ISM: the circumgalactic medium is massive, extended, and “multiphase” (i.e., the gas traced by low-ionization species such as C II and Si II is not in ionization equilibrium with—and is often kinematically distinct from—the gas traced by more highly ionized species such as O VI).

We find that, within 150 kpc of star-forming galaxies, there is at least as much metal mass in a highly ionized phase as remains in their ISM (Tumlinson et al. 2011; Peebles et al. 2014). We also find that there is a substantial mass of cool, low-ionization, circumgalactic gas that appears bound to the halo. Surprisingly, however, this cool material appears to be several orders of magnitude less dense than predicted by “two-phase” models invoking pressure equilibrium with a virialized ($\sim 10^6$ K) ambient medium (Werk et al. 2014). Moreover, the circumgalactic dust-to-metals ratio is somehow at least as high as it is in the ISM, if not higher (Peebles et al. 2014; Peek et al. 2014).

Combined, these results pose a new set of conundrums for astronomers’ understanding of how galaxies acquire and process gas: how do galaxies retain a fixed fraction of their metals despite residing in a wide range of potential well depths? Is this fixed fraction of retained metals a low-redshift conspiracy, or have galaxies retained $\sim 25\%$ of their metals throughout time? How can the CGM maintain a massive reservoir of such low-density yet cool, low-ionization gas that by all accounts should not be pressure supported against falling back into the galaxy on short timescales? In aggregate, what new constraints do these results place on models of galaxy winds, and what new insights can these puzzles of circumgalactic gas physics shed on our understanding of galaxy evolution?

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 Peebles, M. S., et al. 2014, ApJ, 786, 54
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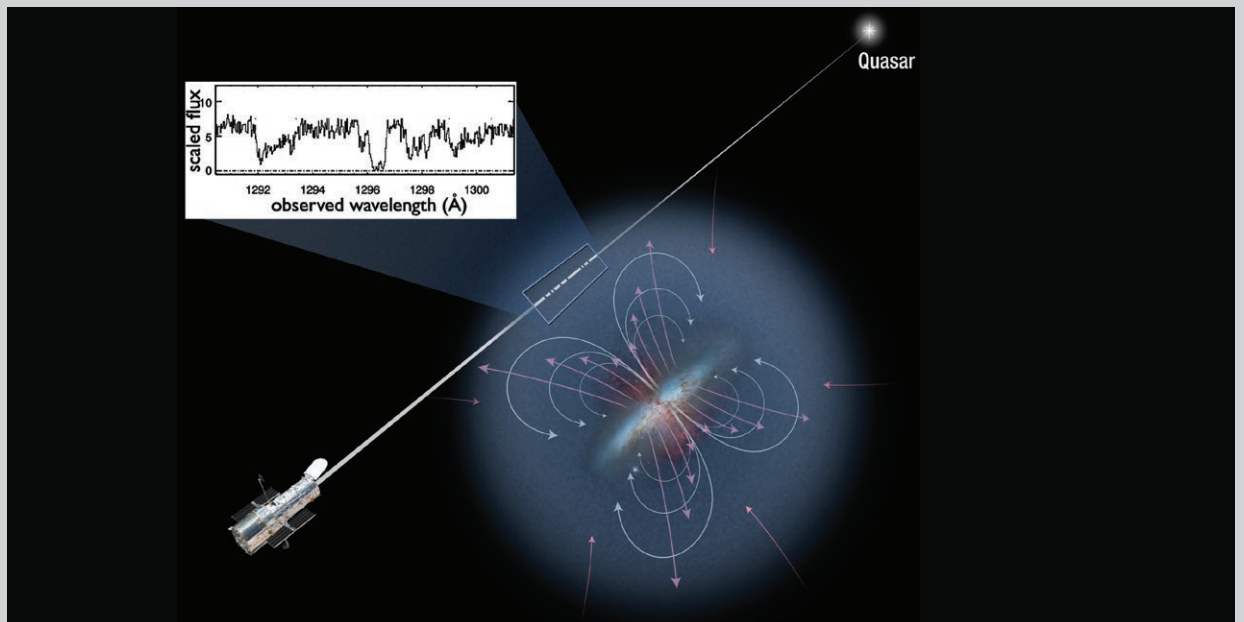


Figure 2: The diffuse gas surrounding galaxies, the circumgalactic medium (CGM) plays host to gas accreting from the intergalactic medium and gas being expelled from galaxies via superwinds that may eventually recycle back into the interstellar medium. Too rarefied to be observed in emission, the CGM is instead studied via absorption along the line of sight to bright background sources, such as quasars. As the dominant transitions are in the rest-frame ultraviolet, the installation of the Cosmic Origins Spectrograph (COS) aboard *Hubble* has revolutionized astronomers’ ability to characterize the CGM at low redshift. Adapted from Tumlinson et al. (2011). Illustration credit: Ann Feild.

The 2014 STScI Spring Symposium: Habitable Worlds Across Time and Space

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The past five years have seen an explosion in the detection of small, rocky planets in orbit around other stars, thanks to NASA's *Kepler* mission and the dedicated effort of ground-based radial-velocity surveys. These transformational discoveries have naturally led to a richer discussion about how astronomers, biologists, and geologists can come together to efficiently determine the occurrence rate of terrestrial worlds capable of sustaining life throughout the Milky Way.

The Institute itself is starting to plan for its role beyond the *James Webb Telescope*, so it was natural for the scientific organizing committee of the 2014 spring symposium to focus on the question of where to look for habitable worlds. Indeed, there was great ferment about what actually constitutes "habitability." We saw an opportunity to drive this debate forward by gathering the foremost experts in a range of topics—from the conditions of the early Earth to the survival of planetary systems beyond a star's evolution into remnants like white dwarfs. The goal was to promote critical thinking about the prospects for habitable planets beyond the traditional treatment of Sun-like stars, and how a broader scope of the search might relate to future NASA missions.

The symposium "Habitable Worlds Across Time and Space" spanned three-and-a-half days, with a total of 27 invited speakers, 9 contributed talks, and 52 posters. The entire program, including slides from the talks, can be found at the Institute's webcast archive (<https://webcast.stsci.edu/webcast/searchresults.xhtml?searchtype=20&eventid=206&sortmode=2>). Additional commentary from participants is available via Twitter (<https://twitter.com/search?f=realtime&q=%23hwats2014&src=typd>).

Seven sessions of the symposium covered: (1) the formation of terrestrial planets, the population of terrestrial planets in the habitable zone around middle-aged stars; (2) the conditions of the early Earth; (3) the formation and evolution of life; (4) the limits to habitability; (5) the potential for life around stars that have evolved beyond middle age, into giants and white dwarfs; (6) the habitability of exo-moons; and (7) the habitability of planets and moons in low-luminosity conditions.

Several important conclusions were drawn at the meeting. These are summarized below and broadly attributed to various speakers.

It was clear that the scientific community is still debating what makes a planet habitable, and how a definition of habitability translates into an optimal search for inhabited planets. There was broad



agreement, however, that at present it is best to focus on planets that could have liquid water on their surface, which is accepted as the main criterion for habitability.

While the basic conditions for forming habitable planets are widely satisfied (P. Armitage, C. Salyk, S. Raymond), the factors determining the details of planetary architecture remain obscure, even in our own solar system. The pathways seem to depend on stochastic interactions between planetary migration and gravitational interactions between the most massive planets in a system (B. Bottke).

Currently, planets found in habitable zones number a few dozen, even with the exact boundaries of a habitable zone still under active debate (N. Batalha). The concept is clearly useful for focusing the discussion of ongoing and future searches.

The concept of a habitable zone depends on assumptions about how the Earth itself works, including the role of plate tectonics (P. Olson, V. Stamenkovic). It is not clear how plate tectonics originated on the early Earth, let alone how continental drift might scale to planets larger and smaller than Earth (D. Valencia).

The prospects for observing planetary systems at a wide range of orbital separations are now quite promising. *Kepler* provides a sample of planets with orbital periods ≤ 1 year. The *AFTA/WFIRST* mission will be complementary, covering the outer edges of planetary systems, with a sensitivity to terrestrial-mass planets overlapping that of *Kepler* (S. Gaudi). The possibility for habitable planets around M dwarfs was discussed, including the issue of whether this class of stars is more or less likely to have habitable planets (E. Guinan). While M dwarfs are locally abundant, and their habitable-zone planets would be easier to detect and characterize than others, it is not clear whether such planets could retain their atmospheres or remain habitable under the influence of tidal forces with their host star (R. Barnes).

Early conditions on the Earth provide one template for how an inhabited world might arise. Conditions on other planets may have been entirely different from the early Earth, however. The complex history of how our current environment arose is entwined with other challenging narratives, such as the formation and evolution of life and the chemical evolutions of the Milky Way and the universe itself. (R. Hazen, S. Mojzsis, M. Gowanlock).

The best bet for discovering life beyond the solar system is the search for biomarkers—spectral biological signatures detected in the total light of a planet (S. Domagal-Goldman, D. Catling). Nevertheless, there is as yet no consensus on what biomarkers would be decisive regarding life. Just as planets in a habitable zone may not necessarily host life, atmospheres found to be out of chemical equilibrium may not require biology to explain them.

The study of stars that have evolved into giants and white dwarfs provide opportunities to study planetary systems in new ways. Results from radial-velocity surveys of giants show that the architecture of planetary systems change with time (A. Wolszczan), and that transit searches of white dwarfs could detect terrestrial planets (E. Agol). White dwarfs are easily polluted by rocky debris from their planetary systems. Such systems offer new avenues for understanding the chemistry of terrestrial-planet formation (B. Gänsicke).

There is evidence that some phases of stellar evolution, particularly in binary systems, may create second generations of planetary systems—an idea that invites further observational and theoretical development (M. Marengo).

Exo-moons may be habitable worlds (R. Lorenz, V. Dobos, D. Forgan). They may receive enough energy—radiative or tidal—from the host planet to sustain balmy temperatures away from a central star. The detection of exo-moons, however, is beyond current technology (A. Barr, K. Lewis).

Further study of our own solar system may suggest promising new targets for inhabited worlds that do not fit in the traditional habitable-zone paradigm. Presently, or at an earlier time, such sites—for example, Ceres (recently shown to be water rich), Europa, and Enceladus—may have possessed liquid water (J. Li, B. Schmidt, A. Murray). Life may also be found in the subsurface, in extraterrestrial oceans.

Participants supported an intense study of Venus to improve our understanding of the limits to habitability, or how habitability may evolve with time. Of all the planets, Venus is the closest in mass and solar distance to the Earth, and at one time it may have had conditions compatible with liquid water on the surface (D. Grinspoon).

Beyond investigating solar-type stars, the meeting demonstrated interest in NASA and ESA pursuing M dwarfs and white dwarfs as targets in transit surveys looking for terrestrial planets. A terrestrial planet discovered around such objects has a deeper transit signal and is thus more amenable to having its atmosphere successfully probed. Even so, such targets are less obvious as hosts of habitable planets since we do not yet fully understand their likely evolution.

The meeting concluded in a spirit of great promise and imminent opportunity to extend recent progress in the field of astrobiology and the study of habitability. Participants foresaw a new generation of investigations to address open questions and fashion a way forward in the search for life across the galaxy. *Hubble* and *Webb* are positioned to answer some of these questions, by dint of their abilities to study solar system bodies in detail, constrain the atmospheric compositions of transiting planets, search for planets by direct imaging, and observe the chemistry and structure of planet-forming disks.

The 2014 STScI Calibration Workshop

Dean C. Hines,¹ hines@stsci.edu, & Robin Auer

The *Hubble Space Telescope* has been operating with its final complement of instruments since 2009. In order to maintain the optimal performance of the observatory, and to develop procedures that maximize the quality and breadth of *Hubble*'s scientific return, the Institute monitors the performance of these instruments, maintains up-to-date calibrations, develops state-of-the-art tools for processing and analyzing science products, and maintains the Mikulski Archive for Space Telescopes (MAST).

A critical responsibility of the Institute is to hold regular calibration workshops to convey progress and to interact directly with the science community. This two-way exchange has proven to be synergistic, and has contributed enormously to the success of the *Hubble* mission. In response to this need and contractual mandate from NASA, the Institute hosted the 7th STScI Calibration Workshop on August 11–13, 2014.

While the latest workshop focused on the current complement of instruments aboard *Hubble*, part of the workshop was devoted to the *James Webb Space Telescope*, for which *Hubble* provides many lessons learned, and many directly applicable solutions to problems that *Webb* will encounter. In addition, the calibration of astronomical instruments and observatories is a rapidly developing field beyond *Hubble* and *Webb*. Therefore the workshop also addressed topics that apply broadly to astronomical calibration in general.



The workshop had 108 registered guests, with 34 invited presentations and 29 contributed posters. Institute director Matt Mountain opened the workshop with a dedication to the late Bruce Woodgate, the PI for the Space Telescope Imaging Spectrograph (STIS), noting Dr. Woodgate's contribution to astronomy in general and to *Hubble* in particular.

Dr. Mountain framed the workshop within the emerging era of “precision astrophysics,” such that our astronomical efforts are achieving precisions and accuracies that were not possible even a decade ago; and calibration has been the key to this advancement.

Invited talks varied in duration from 15 to 35 minutes, but all speakers were given an additional 10 minutes at the end to promote discussion, which further fostered a workshop environment. Some of the highlights of the workshop included: the keynote presentation from Elena Pancino (INAF) on calibration issues confronting the *Gaia* mission, as well as a status update; “Measurement Astrophysics” presented by John McGraw of the University of New Mexico; “Grism Spectroscopy,” presented by Ivelina Momcheva (Yale); and strategies for observing transiting exoplanets, presented by Nikole Lewis (MIT).

¹Chair of the scientific organizing committee and the local organizing committee.

Status updates were presented for each active *Hubble* instrument (Advanced Camera for Surveys, Cosmic Origins Spectrograph, Fine Guidance Sensors, Wide Field Camera 3, and STIS—plus the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), which is not currently available for use but could be revived to provide near-IR capabilities in the event of a failure of WFC3.

New or improved observing methods were discussed, including: use of post-flash to mitigate charge-transfer efficiency issues with the CCDs; spatial scanning with WFC3 for precision photometry and astrometry; COS “blue modes” providing far ultraviolet wavelengths blueward of the approximately 1150 Å lower limit achieved by previous *Hubble* spectroscopic observations; and commissioning of three additional STIS neutral density filters.

Presentations were also made on an eclectic variety of topics, including precision imaging polarimetry with ACS; elevated backgrounds in WFC3 imaging caused by the He 10860 Å emission line in the Earth’s upper atmosphere; coronagraphic imaging and spectroscopy with *Hubble*; observing solar system objects with *Hubble*; status of the *Hubble* Frontier Fields and the *Hubble* Source Catalog; mining archived NICMOS data; persistence in near-IR detectors; and the use of ASTRODRIZZLE for products for *Hubble* and *Webb*.

In lieu of a traditional banquet, a tapas feast featuring gourmet finger food was held in the Azafran Café.

Finally, two mini-workshops were held the day after the main workshop: an ASTRODRIZZLE mini-workshop that provided hands-on demonstrations and tutorials, and a COS mini-workshop that provided a forum for more in-depth discussion of COS-specific calibrations.

The full lists of abstracts for talks and the posters presented at the 2014 STScI Calibration Workshop are available on the workshop website:

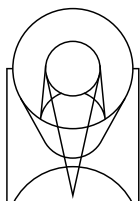
<http://www.stsci.edu/institute/conference/cal14/talksList>

<http://www.stsci.edu/institute/conference/cal14/posterList>.

Archived webcasts of the talks can be viewed on the STScI Webcast Archive website:

<https://webcast.stsci.edu/webcast/searchresults.xhtml?searchtype=20&eventid=212&sortmode=2>

In addition, PDF versions of the posters will be linked to their abstracts.



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For current *Hubble* users, program information is available at:

http://www.stsci.edu/hst/scheduling/program_information.

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Hsiao-Wen Chen, University of Chicago

Michael Cushing, University of Toledo

Annette Ferguson, University of Edinburgh

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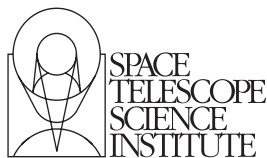
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Calendar

STUC	16–17 April 2015
Spring Symposium,	20–24 April 2015
“ <i>Hubble</i> 2020: Building on 25 Years of Discovery” (STScI)	
AURA BoD	22–24 April 2015
<i>JWST</i> SWG	28–29 April 2015
JSTAC	21–22 May 2015
YAE <i>Hubble</i> STEMfest (STScI)	6 June 2015
Mini Workshop,	29 June–1 July 2015
“The Stellar IMF at Low Masses: A Critical Look at Variations and Environmental Dependencies” (STScI)	
Mini Workshop, “Mocking the Universe” (STScI)	27–29 July 2015
Magellanic Clouds Workshop (STScI)	5–7 October 2015
<i>JWST</i> Science Conference (ESTEC)	12–16 October 2015



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