VOL 20 ISSUE 02

NEWSLETTER

Space Telescope Science Institute

Credit: NASA; K.L. Luhman (Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass.); and G. Schneider, E. Young, G. Rieke, A. Cotera, H. Chen, M. Rieke, R. Thompson (Steward Observatory, University of Arizona, Tucson, Ariz.)

SPRING 2003

Hubble Science Metrics

Georges Meylan, *gmeylan@stsci.edu,* **Juan Madrid, and Duccio Macchetto**

After a decade of Hubble operations, observations, and publications, the Institute decided it was pertinent to measure the scientific effectiveness of the Hubble observing programs. To this end, we developed a methodology and a set of software tools to measure—quantitatively and objectively—the impact of Hubble observations on astrophysical research. We gathered Phase I and Phase II information on the observing programs from existing Institute databases, among them MAST (Multimission Archive at Space Telescope). We gathered numbers of refereed papers and their citations from the Library, the Institute for Scientific Information (ISI), and the NASA Astrophysics Data System (ADS), cross-checking information and verifying that our information was complete and reliable. We organized a unified database with links connecting any specific set of observations to one or more scientific publications. We used this system to evaluate the scientific outcomes of Hubble observations according to type and time.

We could apply a number of parameters to evaluate the impact of Hubble observations on astronomical research. The two most objective parameters are: (i) the numbers of refereed papers based on Hubble observations, which can be measured per year or totaled and correlated with specific observing programs or not, and (ii) the number of citations generated by each paper.

Figure 1 (see page 3) shows the histogram of the number of refereed papers, by year, based on Hubble data that appeared in the main professional journals: *Astrophysical Journal, Astronomical Journal, Astronomy and Astrophysics, Monthly Notices of the Royal Astronomical Society, Publications of the Astronomical Society of the Pacific,* and *Nature.* Following a strong and regular increase of publications during the first eight years of Hubble, the number of papers keeps increasing, although at a slower pace, during the last four years, to reach a value of 499 for the year 2002.

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Courage and Purpose

Steven Beckwith

We had almost come to take for granted the precision with which NASA launches astronauts into orbit and brings them safely back home. The fiery breakup of Columbia over Texas showed us how daring each mission really is.

On April 24, 1990, STS-31 carried the Hubble Space Telescope aloft to begin its mission of astronomical discovery. The flawed mirror, discovered only after it was in orbit, would have doomed any telescope that could not be serviced. Yet in December 1993, astronauts aboard STS-61 went back to fix the observatory and make it the superlative instrument that it is today.

Not only has Hubble delivered images of the universe that captivate the entire world; it has kept getting better as NASA has installed new instruments in subsequent servicing missions. In February 1997, STS-82 brought up the infrared camera, NICMOS, and the advanced spectrograph, STIS. In December 1999, STS-103 refurbished Hubble's guidance system and computers. In March 2002, STS-109 installed the Advanced Camera for Surveys (ACS) and revived NICMOS with a novel cooling system. This feat recalled memories of the historic mission in 1993 to fix the telescope itself.

Hubble has become an icon of scientific progress and technical innovation, and its scientific impact continues to grow at an even faster pace than in the past.

Where would astronomy be without a shuttle program and astronauts to repair and upgrade Hubble? We would not have the Hubble Deep Field. Nor the distances to high-redshift supernovae making the case for dark energy. Nor the images of circumstellar disks making planet formation credible. Nor the first detection of the atmosphere of an extrasolar planet. We could not visualize the awesome Eagle Nebula, the auroras on Jupiter and Saturn, nor the rings around SN1987a, and we would not know the value of the Hubble constant from Cepheids in Virgo galaxies. Without the shuttle astronauts, we would not have had this window on the universe at all.

But—thanks to STS-31, STS-61, STS-82, STS-103, and STS-109—Hubble exists, and all it has accomplished is real. Today, Hubble is the world's most recognized and admired scientific instrument. It has helped astronomy become the foremost science in the public interest, with a gift for educating and inspiring. And people worldwide are excited to be learning where the universe came from and what it is all about.

Hubble has accomplished so much—and will accomplish so much more—because astronauts are willing to risk their lives for science, for a telescope. We are grateful that they go into space to improve our lives and our culture by enabling the discovery of new knowledge. We are both proud of and humbled by their courage and purpose, and we will always remember their sacrifices when we think of Columbia's last crew. Ω

The current total is over 3570 refereed papers. During the last four years, the number of refereed papers based on Hubble data constitutes about 7% of all refereed papers published in astrophysics, as represented by these journals.

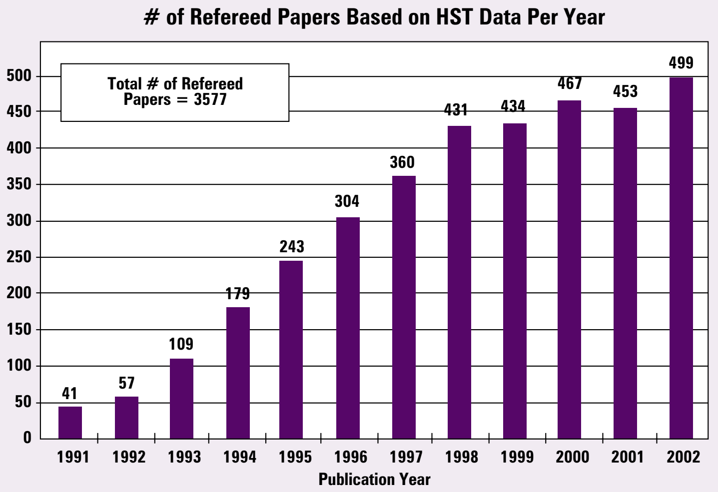

Figure 1: *Histogram of the number of refereed papers, by year, based on Hubble data that appeared in the main professional journals.*

Figure 2 shows the histogram by year of the mean number of citations of refereed papers based on Hubble data. For comparison, the yellow curve shows the mean number of citations for all refereed astrophysics papers. This shows the impact of Hubble science clearly: the average paper based on Hubble data received twice the citations of the average astronomy paper.

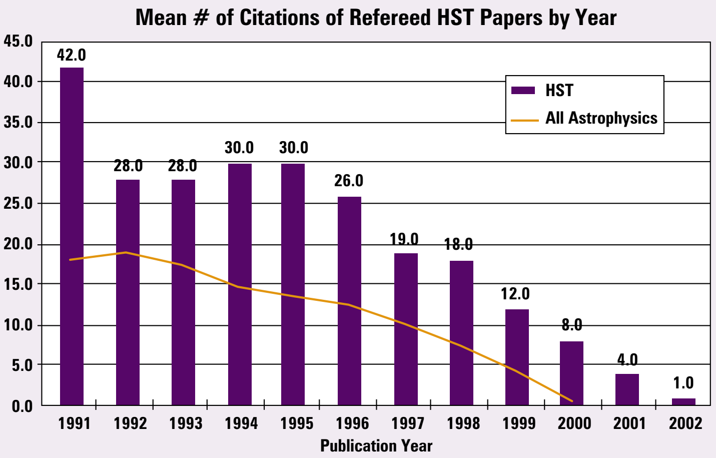

Figure 2: *Histogram by year of the mean number of citations of refereed papers based on Hubble data.*

Figure 3 (see page 4) displays the histogram by year of the number of refereed papers based on Hubble data that have not been cited. Understandably, there is a time delay between the publication of a scientific paper and the first paper citing it. After allowing a few years time, only about 2% of the Hubble based papers have no citations, whereas about one third of all refereed papers in astrophysics are never cited.

Figure 4 (found on page 4) shows the histogram by year of the number of refereed papers generated by programs in the early Cycles 4 and 5. The peak number of publications occurred about 3 years after the cycle start, delayed by data acquisition, data reduction, analysis, and the publication process.

To study the impact of Hubble programs as a function of the number of allocated orbits, we divided them in bins of small (1 to 50 orbits, with sub-bins 1 to 10, 11 to 20, and 21 to 50 orbits), medium (51 to 100 orbits) and large programs (over 100 orbits).

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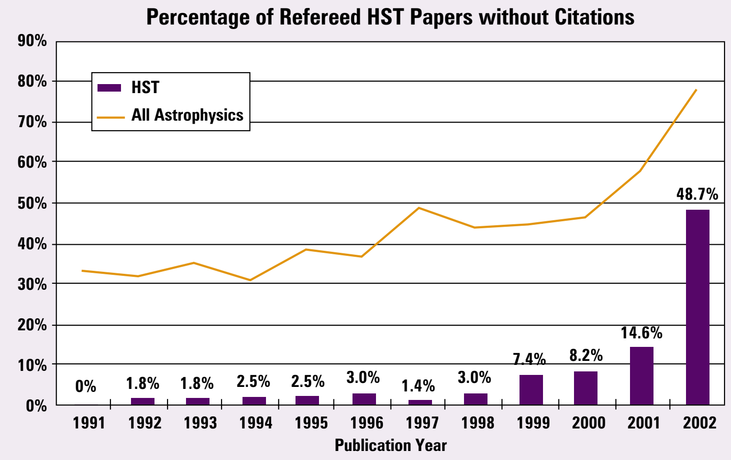

Figure 3: *Histogram by year of the number of refereed papers based on Hubble data that have not been cited.*

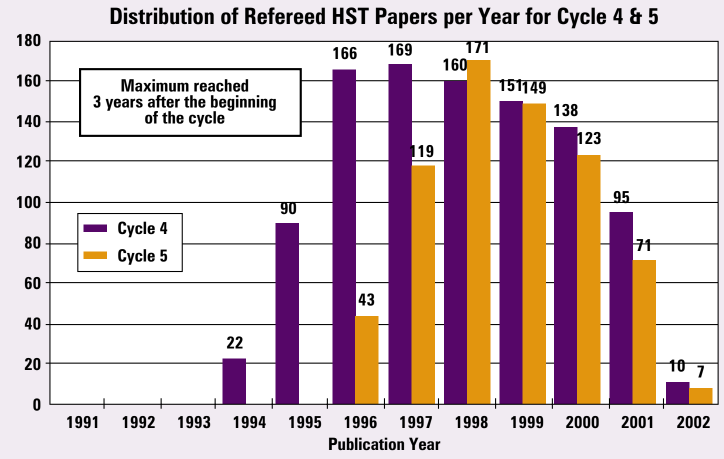

Figure 4: *Histogram by year of the number of refereed papers generated by programs in the early Cycles 4 and 5.*

Figure 5 shows the histogram of the mean number of refereed papers generated per program versus program size. On average, large programs have generated five times more papers than small programs.

Figure 6 shows the histogram of the mean number of refereed papers generated per orbit. On

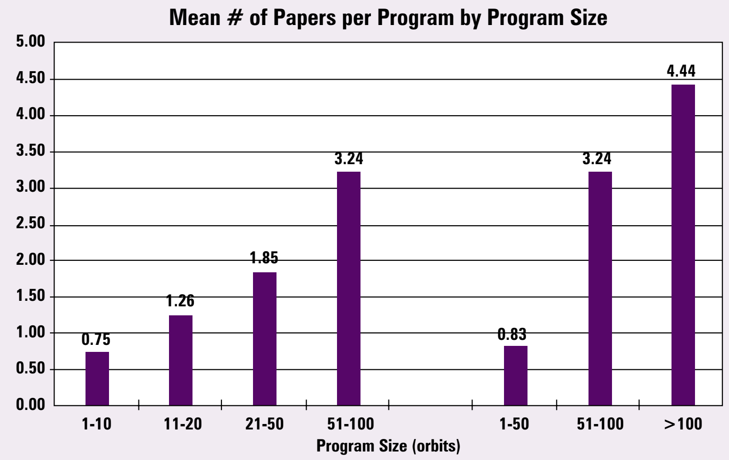

Figure 5: *Histogram of the mean number of refereed papers generated per program versus program size.*

average, large programs have generated three times fewer papers per orbit than small programs. However, it must be pointed out that large programs typically observe significantly fainter targets, which requires more orbits.

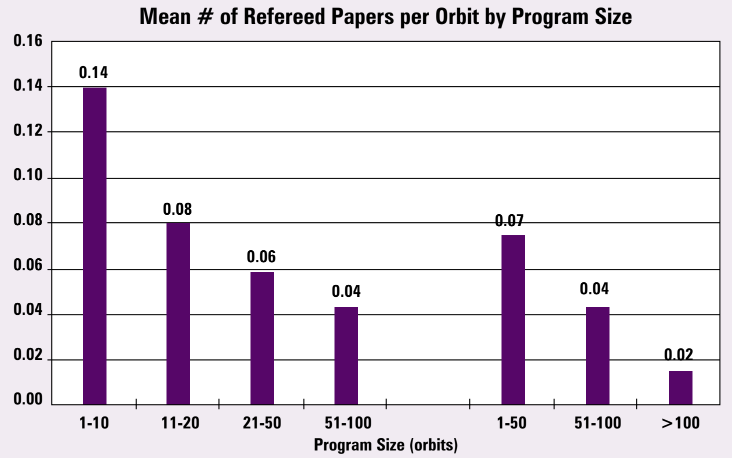

Figure 6: *Histogram of the mean number of refereed papers generated per orbit.*

Figure 7 shows the histogram of the mean number of citations per refereed paper according to program size. On average, larger programs produce more citations, with large programs producing about 30% more citations than small programs.

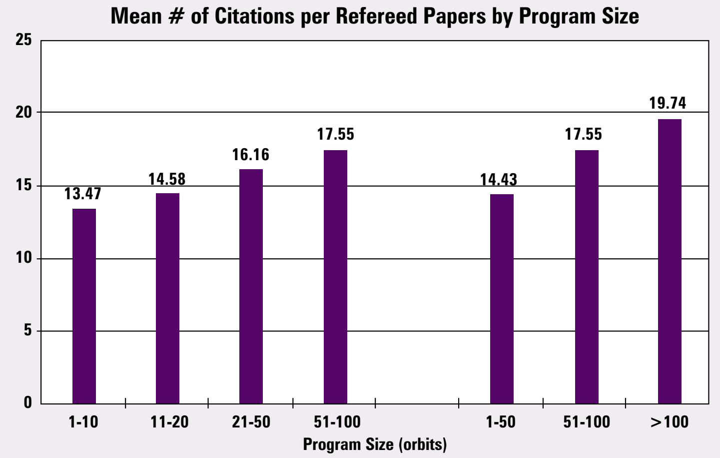

Figure 7: *Histogram of the mean number of citations per refereed paper according to program size.*

For 1991 to 1999, ISI identified the 200 'high impact papers' (HIPs) in each year that accumulated the largest numbers of citations from 1991 to 2002. Figure 8 (see page 6) shows the histogram by year of the fraction of HIPs based on Hubble data. The effect of the successful deployment of COSTAR and WFPC2 on the quality of refereed papers between 1993 and 1994 is obvious. Since 1994, Hubble has consistently generated nearly 10% of all HIPs—larger than any other astronomical facility.

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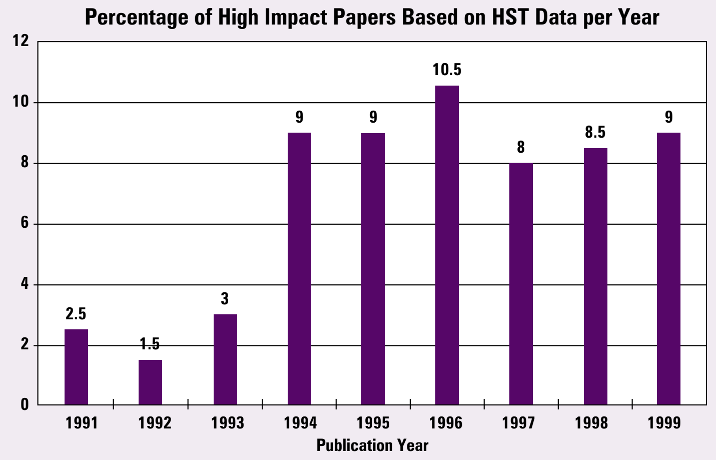

Figure 8: *Histogram of the percentage of High Impact Papers that were based on Hubble data.*

We will use our tools to update these Hubble science metrics on an ongoing basis. This activity will help shape Hubble scientific opportunities in the future. Ω

Amazing ACS

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

The Advanced Camera for Surveys (ACS) continues to amaze with beautiful, high quality data. No fewer than five groups announced their ACS results in press releases at the January 2003 meeting of the American Astronomical Society in Seattle.

One group, led by Narciso Benitez, released Figure 1, which is an image of one of the most massive galaxy clusters known—Abell 1689. It shows a large number of arcs caused by gravitational lensing. Studying the arcs will improve the determination of the dark-matter distribution of the cluster. Also, gravitational magnification permits study of the many background galaxies and should provide new insights into their properties. (**http://hubble.stsci.edu/newscenter/archive/2003/01/**)

Haojing Yan and his team reported that deep ACS images reveal numerous faint objects, which they believe are young star-forming galaxies seen at a time when the universe was about seven times smaller than today and less than a billion years old. (**http://hubble.stsci.edu/newscenter/archive/2003/05/**)

Bill Keel and his team presented images of the galaxy 0313-192, the first spiral galaxy known to produce a giant radio-emitting jet. (**http://hubble.stsci.edu/newscenter/archive/2003/04/**)

The two other press releases showcased the first results of the powerful ACS coronagraph, which offers better contrast and resolution than previous instruments.

Andre Martel and his team released the best view yet of the host galaxy of the nearby quasar 3C 273. (**http://hubble.stsci.edu/newscenter/archive/2003/03/**)

Mark Clampin and his team used the coronagraph to study the dust disk around HD 141569A, which is a young star about 5 million years old. This disk may be the type that forms planets. (**http://hubble.stsci.edu/newscenter/archive/2003/02/**)

We recently increased the power of the ACS coronagraphic mode by implementing improved observational procedures. The new commanding yields more consistent and accurate target acquisitions and deals better with small drifts of the coronagraphic spots due to gravity release, as described in the recent ACS Instrument Science Report, ISR 02-11 by John Krist. (**http://www.stsci.edu/hst/acs/documents/isrs/isr0211.pdf**)

ACS will continue to be a focus of attention in Cycle 12. More than half of the proposals received by the January 24 deadline called for the use of ACS. Also, plans are shaping up for observations of an ACS Ultra Deep Field (UDF) in Cycle 12. (**http://www.stsci.edu/science/udf/**)

The UDF observations will use Director's Discretionary time, as did the original Hubble Deep Field (HDF) campaigns. For 410 orbits, the ACS will image a single field within the Chandra Deep Field South. The field will probably include a type II QSO and a galaxy at a confirmed redshift of $z = 5.8$. The observations will use four filters: F435W (Johnson B; 55 orbits), F606W (broad V; 55 orbits), F775W (SDSS i; 150 orbits), and F850LP (SDSS z; 150 orbits). The observations will go 1 to 1.5 magnitudes deeper than the observations of the HDFs. The UDF will probe galaxies at redshifts $z > 6$, near the tail of the reionization epoch, by taking advantage of the spectral resolution and depth of the F775W and F850LP data set. At lower redshifts, it will provide some of the strongest constraints to date on the faint end of the luminosity function and help to address the effect of cosmological surface brightness dimming on observed galaxy morphologies and the cosmic star-formation history.

Figure 1: *ACS obtained this stunning image of Abell 1689, one of the most massive galaxy clusters known. Gravitational lensing distorts faint background galaxies into thin arcs, yielding a wealth of information on both the cluster and the background galaxies.*

The Institute received twenty archival proposals in Cycle 12 for analysis of the UDF data. We expect these data to become an important resource for the community in the years to come.

At the Institute, we continue to focus our ACS-related software efforts on drizzling tools. Because of its large geometric distortion, ACS data analysis is fundamentally different from that of most imaging cameras. For example, the projections on the sky of the Wide Field Camera (WFC) detector axes are 3.5 degrees away from being perpendicular. The ACS development team did not include optics that could have corrected this distortion in order to maximize overall throughput. Therefore, the distortion must be corrected after the fact, during data analysis. We developed the innovative pipeline program PyDrizzle to simultaneously

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combine dithered images and correct for geometric distortion. The resulting data are both astrometrically and photometrically accurate. We are now developing tools that can deal with other complexities.

We recently released a beta version of MultiDrizzle (**http://stsdas.stsci.edu/pydrizzle/multidrizzle/**). Users can download this script and run it on pipeline-reduced data at their home institution. It runs PyDrizzle iteratively to flag and remove cosmic rays optimally. MultiDrizzle even works for data sets that have only a single exposure at each dither position. We are investigating additional future upgrades of MultiDrizzle.

Our ACS calibration programs are progressing well. We improved procedures for the routine creation of bias and dark reference files. We are calculating improved bias and dark images for the first year of ACS operations, which can be applied retroactively. We modified the sensitivity tables for WFC, especially at the reddest wavelengths. The tables should now be accurate to approximately 1% at all wavelengths. Similar improvements for the HRC sensitivity tables are in progress. We modified the default aperture positions of the ramp filters to improve throughput. We improved geometric distortion tables for the polarizers.

Some observatory-wide improvements have benefited ACS data. Engineers re-aligned the Fine Guidance Sensors in October 2002, which improved the astrometric accuracy of pipeline-reduced data. Also, they moved the telescope's secondary mirror in December 2002—the first time since 2000—to re-optimize the HST focus.

As always, the latest news about ACS can be found at **http://www.stsci.edu/hst/acs/**. Ω

News from the Multi-Mission Archive at STScI (MAST)

Paolo Padovani on behalf of the MAST team, *padovani@stsci.edu*

The Hubble data archive now contains about 11.8 terabytes of data in about 299,000 science data sets. The archive ingests an average of 15 gigabytes per day. Lately, researchers have been retrieving data from the archive at a rate 3 times higher, about 46 gigabytes per day.

Hubble, IUE, and EUVE Proposal Abstracts Search

MAST has implemented a new interface to search the Hubble, International Ultraviolet Explorer (IUE), and Extreme Ultraviolet Explorer (EUVE) proposal abstracts. Users may now search on words or strings in the abstracts and titles, and by PI name or proposal ID, individually or in combination. Users may also enter words or phrases, separated by commas, in the search box on the left menu of each mission page to search abstracts. The user can access the search form and get help on search syntax at:

http://archive.stsci.edu/hst/abstract.html
http://archive.stsci.edu/iue/abstract.html
http://archive.stsci.edu/euve/abstract.html

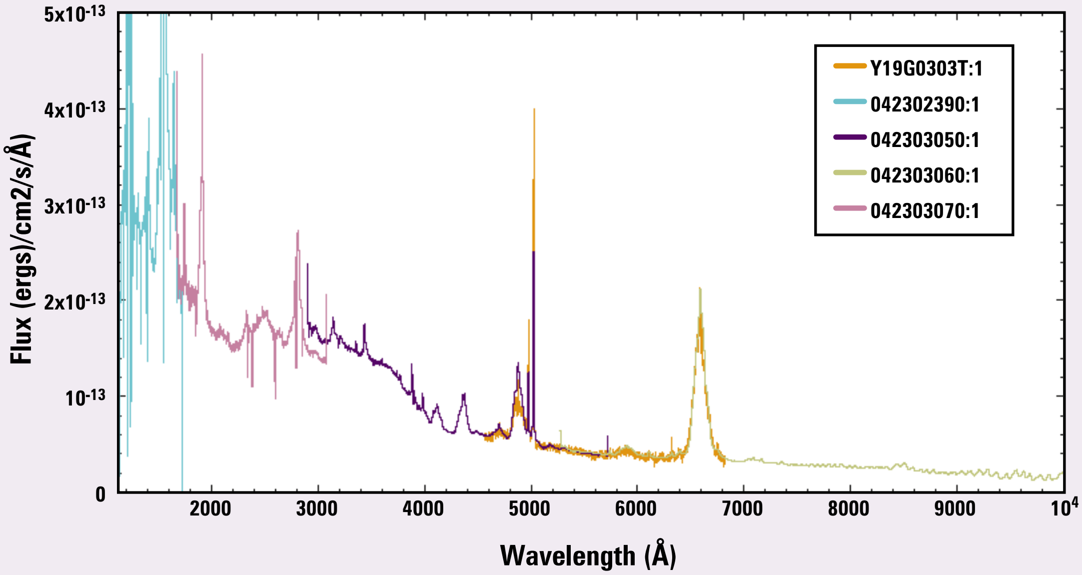
These pages are also accessible from the main mission pages from the Archive Services (Hubble) and Search & Retrieval (IUE and EUVE) subheadings.

The Hubble abstract search is now faster and improved, and the IUE and EUVE abstract searches are new. The IUE abstract database contains abstracts for most of the IUE proposals that were part of the U.S. program. European and British IUE proposals were not available for inclusion. However, the IUE abstract database does contain titles (and authors) for all programs, so searching titles may still be useful for archive users interested in looking for specific projects. The EUVE abstract database is mostly complete. MAST is planning to make a Far Ultraviolet Spectroscopic Explorer (FUSE) proposal abstract search available soon.

Co-Plotting Hubble Spectra

In the Spring 2002 issue of this Newsletter, we announced the availability, for several MAST missions, of a tool to co-plot multiple spectra from the search-results page. We have now extended this feature to the Hubble search page (**http://archive.stsci.edu/cgi-bin/hst**). For example, archive users can now easily compare observations of the same target taken at different times or with different instruments, or Hubble spectra of different targets.

After the user selects preview spectra on the search-results form, the co-plotting script extracts the fluxes and wavelengths and plots the spectra on an HTML form as a GIF-format image. The form offers options to redraw the plot with different scaling factors. Currently, the user can co-plot up to 15 spectra, with each spectrum rendered with a different color and accompanied by descriptive information (see Figure 1).



PLOTTED DATA SETS:

Mission:	Data set:	Target:	Wavelength Range (Å):
FOS	Y10G0303T	NGC4151	4569-6817
STIS	O42302090	NGC4151	1124-1722
STIS	O42303050	NGC4151	2904-5714
STIS	O42303060	NGC4151	5272-10267
STIS	O42303070	NGC4151	1671-3076

Figure 1: *A co-plot of four Space Telescope Imaging Spectrograph (STIS) spectra and one Faint Object Spectrograph (FOS) spectrum of the Seyfert 1 galaxy NGC 4151 covering the 1,100 - 10,000 Ångstrom range.*

MAST Support for NVO Standards

The MAST search interface now allows results to be output not only in HyperText Markup Language (HTML), ASCII, and Excel but also in VOTable format. The National Virtual Observatory (NVO) has proposed the VOTable format as the Extensible Markup Language (XML) standard for representing a table. (See **http://www.us-vo.org/VOTable/**.) NVO and its partners designed VOTable as a flexible storage and exchange format for tabular data, with particular emphasis on astronomical tables. The search interface now also supports 'simple cone searches' as specified by NVO. (See **http://voservices.org/cone/default.asp**.) MAST is registering this feature as an available service with the NVO.

FUSE Quick-Look Previews and New "Minimal" Retrieval Option

The FUSE (Far Ultraviolet Spectroscopic Explorer) project will reprocess all its data through a new processing pipeline over the next six months, generating preview plots as new data products. As the data are processed and become public, MAST will make these comprehensive previews available. An example of the new FUSE previews

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can be seen at: **http://archive.stsci.edu/cgi-bin/mastpreview?mission=fuse&dataid=Z9073601000**. All observations processed since last September have used the new pipeline, but most are still proprietary.

As the reprocessing effort will take several months to complete, the FUSE project has generated a simple quick-look preview from the existing archive, to use until the data are fully reprocessed.

At our request, the FUSE project has also agreed to a package of 'minimum recommended data files' for users who do not want to receive unneeded files. This is now the default retrieval option.

New Archive Storage

The Institute has purchased a new EMC 'storage area network' (SAN) for the archive and data processing systems. It is a fully redundant, mirrored disk array with high availability and a fiber switch. Over the next few months, we will connect this system to our current operational machines and move over data that are currently only stored on the magneto-optical disks. This new storage will lessen our dependence on the jukeboxes and allow us to cache many highly requested files to speed on-the-fly recalibration. We expect the installation process to involve minimal downtime and to be transparent to users. Ω

Re-planning JWST

Roelof de Jong, *dejong@stsci.edu,* **Margaret Meixner, George Rieke,**
Peter Stockman, and the MIRI team*

In the last six months, NASA has selected all major James Webb Space Telescope (JWST) partners, including the prime contractor, the instrument teams, and the Science Working Group (SWG). The JWST project is currently going through a re-plan activity to make sure that all designs and ideas are well matched and that the whole project fits within the budget profile. Elimination of the Mid-Infrared Instrument (MIRI) is one of the options being considered to reduce costs. In this article we provide more information on the current JWST re-plan activities and on MIRI's science drivers and design.

The JWST Budget Crisis

This is a watershed moment for JWST, one in which science capabilities, development responsibilities, and verification plans will be established or lost. With all the major development partners selected, the JWST project is ready to begin the detailed design of the observatory (Phase B). Before Phase B can begin, however, the project must prepare a spending plan that fits within the funding levels of NASA Headquarters (HQ) and that agrees with independent estimates.

Like many other NASA missions, JWST costs have been a major challenge. In 1996, the HST & Beyond report recommended a cost target of $500M for a four-meter class telescope. For the original feasibility studies, NASA maintained that target, hoping to achieve it for an eight-meter deployable telescope using new technologies and a 'better, faster, cheaper' approach. The initial development cost estimates ranged from $400 to $550M, which did not include launch, integration and test, or contingency. To achieve the full funding, NASA approached the European Space Agency (ESA) and the Canadian Space Agency to become international partners, providing approximately $250M (1996 dollars). Also, it selected the Institute as the Science and Operations Center to achieve savings through the use the Hubble infrastructure and software. Nevertheless, the U.S. portion of the estimated budget soon grew to ~ $1B (in approximately 2006 dollars) as the elements of the program became better defined and NASA's development approach became more traditional following the failures of two Mars missions. In its request for the prime contract proposal, the JWST project reduced the aperture goal to six meters, and, in the science Announcement of Opportunity, it reduced the numbers of pixels available for the Near Infrared Camera by 25%.

In November 2002, Anne Kinney, the director of the Astronomy and Physics Division at NASA HQ, requested that the project provide a number of options for implementing the JWST mission. In addition,

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* *G.H. Rieke (lead, U. Arizona), G.S. Wright (co-lead, UK ATC), F. Bortoletto (Obs. Astro. di Padova), T. Greene (NASA Ames), T. Henning (MPIA), P.-O. Lagage (C.E.A.), M. Meixner (STScI), and E. Serabyn (Instrument Scientist, NASA JPL), with additional assistance from B. Rauscher (STScI) and E. van Dishoeck (Univ. of Leiden).*

Kinney provided guidelines: the primary mirror should be six-meter class; the funding required for the next 4 fiscal years should fit within a specified profile; the overall U.S. cost for the construction and launch of the observatory should be less than $1.6B; the mission should provide adequate contingency levels (30% for development) and satisfy external reviews; and one of the recommended options should be ready to launch in 2010.

Anne Kinney's request led to an in-depth NASA study of the project plans with participation of the SWG, the prime contractor (Northrop Grumman Space Technologies–NGST!), the Institute, and other development partners. Phil Sabelhaus, the newly appointed project manager, set a goal of January 15 for the studies to be completed, so that he could provide a final recommendation to HQ by the end of February. This article is based upon his most recent briefing to the SWG, on 13 February. The final project recommendations, the SWG's response, and Kinney's decisions for the mission should be known by April.

Phil Sabelhaus took a two-step approach to the re-plan effort. The first step, the most time-consuming, involved merging the plans developed independently by NASA and Northrop Grumman and considering alternative approaches for acquiring major elements of the observatory that could reduce cost, risk, or schedule. The elements under reconsideration were the mirror (its diameter, segmentation, and shape), the flight computers, the launch vehicle, the instrument module, the science instrument capabilities, the infrared detectors, and the integration and test plans and equipment. At HQ's suggestion, the project also examined the cost of providing MIRI and MIRI's impact on the design and cost of the observatory. In the second step, Sabelhaus used the results of these studies to develop a series of options to respond to Kinney's request. In this step, he received advice from a small set of stakeholders and the SWG.

On January 15, NASA and Northrop Grumman personnel presented the final results of the studies to the project. They reported that only minor cost savings could be achieved by merging activities or reassigning development responsibilities. For these savings and based upon his experience with the Earth Observing System developments, Sabelhaus has reallocated some responsibilities to the prime contractor and the science instrument teams, making these efforts more self-sufficient. In addition, as another cost-cutting measure, he reduced the level of support staff at GSFC by 25%.

The expendable launcher was a pleasant exception to the bad news on costs. Here, ESA has tentatively agreed to provide an Ariane V rocket, which would be its second major contribution to JWST. (ESA also provides the Near Infrared Spectrograph, NIRSpec.) The ESA-provided launch saves NASA $120M and improves launch performance, delivering more mass to orbit.

The technical studies in the re-planning exercise had several interesting results. A joint Northrop Grumman and NASA analysis showed that the addition of the MIRI did not impact the design of the observatory beyond the cost and mass of a third instrument. A separate study showed that the savings from reducing the size of the primary mirror would be approximately proportional to the area—approximately $3M per square meter. For primary mirror areas less than about 25 square meters (equivalent to a 6 m circular aperture with central obscuration), the primary mirror design could use only 18 segments instead of 36, which would reduce the risk of manufacturing. Finally, the optimum integration and test plan would call for more than six months of cryogenic testing, with several additional months held as contingency. If the test plans were to be compressed, NASA and Northrop Grumman engineers foresaw significant risk that problems late in the program would demand more testing and delay launch.

At a meeting in late January, the SWG heard the results of the studies and Sabelhaus's preliminary set of four options for the JWST program. The following description of the four options reflects a second briefing of the SWG, by telecon on 13 February:

Option 1. In order to reach a 2010 launch date within the current budget, the project must eliminate the MIRI, reduce the mirror size to 22.7 square meters, and reduce the fields of view of the NIRCAM and NIRSpec instruments by 75% and 88% respectively. Option 1 has also an abbreviated integration and test program. No one, including HQ, favors this option.

Option 2 retains the MIRI (the highest priority of the SWG) and still launches in 2010. This option adds over $100M in costs and significantly exceeds the available early funding.

Option 3 maintains the science content (29 square-meter mirror and current instrument budgets), allows for a robust integration and test program, and delays development until the HQ funding is adequate. This option delays launch by more than two years (into late 2012 or early 2013) and exceeds the total $1.6 B budget. While the SWG endorses this approach, it seems unlikely that HQ will approve such a significant delay in launch and increase to the overall cost.

Option 4 requests additional near-term funding to provide for an earlier launch and will also be difficult for HQ to approve, given the launch delays in other programs and the still unknown impact of the Columbia accident.

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The early funding limits appear to be the biggest challenge to the JWST mission. Since February, the Project has decided to reduce the area of the primary mirror to 25 square meters and streamline the development and testing schedule without adding significant risk to a 2011 launch date. The SWG explored several cost savings in the science instruments. This process, while unable to meet the funding guidelines in FY06-07 without loss of major instrument capabilities, has increased NASA HQ's confidence in the budget and support for the science program. As this newsletter goes to press, Anne Kinney has indicated her commitment to a strong instrument complement for JWST that includes the MIRI. In order to enable the JWST science while keeping the overall cost cap, she will rephase (borrow) FY06-07 funding from within the programs that she oversees and reduce the JWST budgets in later years. Using this revised budget profile, the Project will complete the planning of the observatory and instrument development this summer.

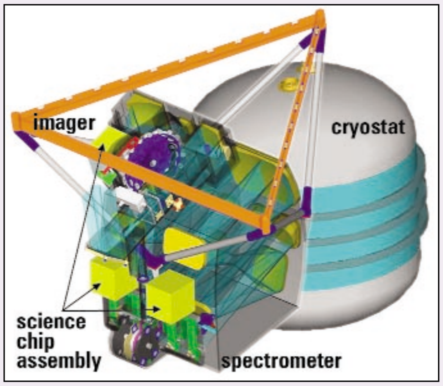

Figure 1: *The MIRI optics module* **(left)** *and solid hydrogen cryostat* **(right)***. The imager has one detector, identified as a yellow box, and is located on top of the IFU spectrometer which has two detectors, identified as two yellow boxes.*

MIRI Design and Science

Over the past year, a team of U.S. and European scientists and engineers has developed an engineering design for MIRI. The European consortium will contribute the optical bench and the U.S. will provide the detectors and electronics. The U.S.-European team will oversee MIRI's construction.

MIRI will provide imaging and spectroscopy over the $\lambda = 5$ to 27 μm wavelength range. Its design consists of two main modules, an imager and an integral field unit (IFU) spectrometer. MIRI is actively cooled by either a cryo-cooler or a cryostat. (See Figure 1.) Both the imager and spectrograph are fed by common optics from a single pick-off mirror located close to the telescope focal plane.

The MIRI imager will provide broad and narrow-band imaging, phase-mask coronagraphy, Lyot coronagraphy, and low-resolution ($R \sim 100$) slit spectroscopy using a single 1024 x 1024-pixel, Si:As sensor chip assembly (SCA). The imager will be diffraction limited at 6 mm with a pixel scale of 0.1 arcsec and a field of view of 102 x 102 arcsec.

The integral field spectrograph will obtain simultaneous spectral and spatial data on a relatively compact region of sky. Its design uses four image slicers to provide $R \sim 3000$ integral field spectroscopy over a $\lambda = 5$ to 27 μm wavelength range. The IFUs provide four simultaneous fields of view, ranging from 3.5 x 3.5 arcsec to 7.5 x 7.5 arcsec with increasing wavelength, with pixel sizes ranging from 0.127 to 0.631 arcsec. The spectrograph uses two 1024 x 1024-pixel, Si:As SCAs, which are sensitive from $\lambda = 5$ to 27 μm. (There is a goal to extend the detector's long wavelength cutoff to $\lambda = 28.3$ μm.) The spectral data cover the entire wavelength range using four IFUs and four grating positions.

Due to JWST's cold operating temperature and large primary mirror, MIRI will provide an immense discovery space and deliver awesome power for studying the mid-infrared sky. Figure 2 illustrates the tremendous gains over SIRTF and over 8-meter and 30-meter infrared-optimized ground-based telescopes. MIRI's unprecedented sensitivity will allow astronomers to make important progress in all four science themes that define JWST: (1) detection of the 'first light'; (2) assembly of galaxies; (3) birth of stars and proto-planetary systems; and (4) evolution of planetary systems and the conditions for life. The following paragraphs expand on these themes.

One of the main science goals of JWST is the discovery of 'first light'—detecting the first sources of light after recombination. Theoretical speculations about the nature of these first light sources cover a wide range of possibilities, with large uncertainties in mass, redshift, and even the source of energy. MIRI observations are critical to identifying these first-light objects reliably (see Figure 3). MIRI observations are needed both to distinguish objects that are truly forming their first stars from objects that have a longer history of star formation. They are also needed to distinguish between stellar-powered and black-hole-powered sources and to probe the properties of the first quasars.

During the assembly of galaxies, interactions between galaxies can trigger powerful episodes of star formation and activate accretion onto nuclear supermassive black holes, creating active galactic nuclei (AGN). Between 10 and 100 million years after the first major episode of massive star formation, enough heavy elements created in the young stars will have been ejected into the interstellar medium to significantly increase its metallicity. Much of the mass of heavy elements may be locked up in dust, which will obscure the starburst and AGN activity at the optical and near-infrared wavelengths.

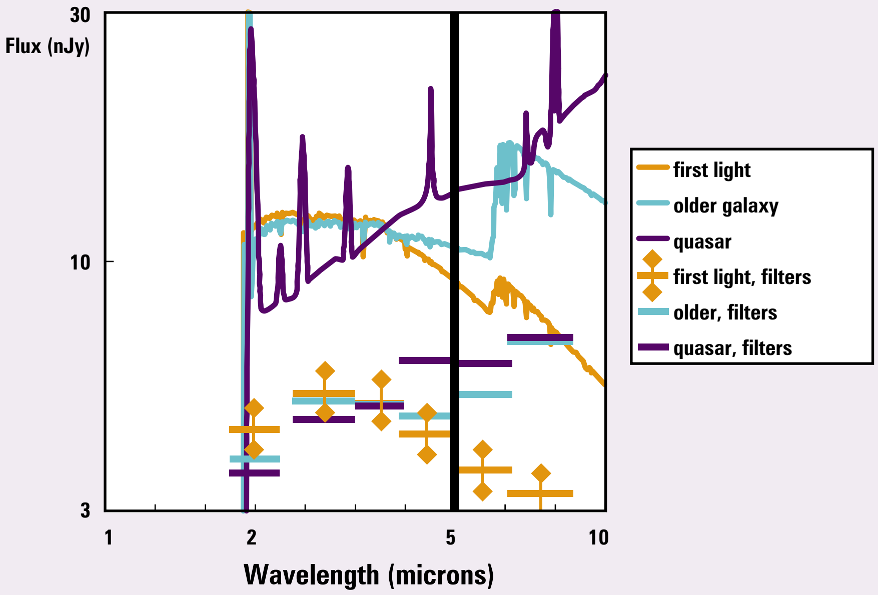

Figure 2: *Gain in survey speed of MIRI on JWST over Gemini, SIRTF, and a 30-meter diffraction limited, ground-based telescope. Survey speed includes the benefits of sensitivity, field of view and angular resolution for mapping point sources over large areas on the sky. For the 30-meter class telescope, the performance at the shorter wavelengths depends critically on Multi-Conjugate Adaptive Optics and hence has not been included in the figure.*

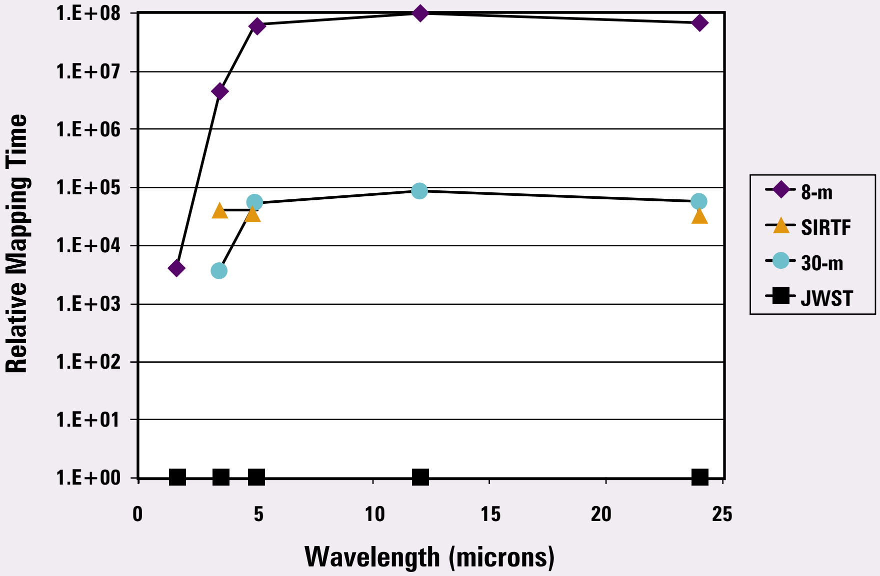

Figure 3: *Model spectra of three objects:* **(1)** *a first light galaxy with a starburst at z = 15.2;* **(2)** *an older galaxy with two bursts of star formation, one at z ~ 20 and a second at z = 15.2; and* **(3)** *a typical quasar. All sources are at a redshift of z = 15, and it has been assumed that the Lyman-α forest strongly attenuates their outputs short of the Lyman-α wavelength. The horizontal bars indicate the Near-Infrared Camera (NIRCam) and MIRI filter bands at wavelengths below and above 5 micron respectively. We show the relative signal levels that we would detect through these filters for the three model sources, offset for clarity. Error bars of ± 10% are also shown on the first light detections.*

Astronomers need MIRI to probe the obscured activity. They will be able to observe mid-infrared fine-structure lines (up to redshift z ~ 2.5) and near infrared coronal lines at higher redshifts. To observe the assembly of high redshift systems (z ≥ 3), MIRI will image the redshifted near-infrared light from red giants and supergiants, which generally represent most of the stellar mass. Astronomers will use MIRI spectroscopy of the (redshifted) CO first-overtone bandhead at 2.3 µm, produced by these giant stars, to investigate the galaxy dynamics and estimate the dark-matter content.

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Dusty molecular clouds enshroud the birth of stars and proto-planetary disks. Interstellar dust is particularly transparent in the wavelength range of MIRI. Using MIRI imaging and spectroscopy, astronomers will be able to probe deeply into the warm interiors of protostars, revealing their currently unknown structure. They will use MIRI observations of the structure and kinematics of collapsing protostellar clouds to test binary star formation and fragmentation models. Also, they will use MIRI to image protoplanetary disks at exquisite resolution. Furthermore, because many organic spectral features occur in spectral windows of low interstellar dust opacity in the MIRI wavelength range, MIRI spectroscopy will probe the mineralogy and the state of the gas in proto-planetary disks, including the raw materials for life, such as water and hydrocarbons.

Debris disks are the most observable manifestation of a planetary system because they dominate the surface area. The current MIRI design can image the nearest examples in detail, revealing the composition and structure of the dust and gas. Dynamical models for debris disks predict that massive planets will have a dominant effect on their structures (see Figure 4). With MIRI, astronomers will be able to deduce the presence of these planets indirectly, from the structure in the debris disks, and in many cases image the planets directly using the coronagraphic capabilities.

Kuiper Belt Objects (KBOs) are not only an important constituent of the Solar System, but they also represent the largest members of the debris system of the sun. MIRI radiometry of KBOs, combined with optical measurements of reflected light, will measure their albedos and constrain their composition. Astronomers will want to use MIRI spectroscopy of small bodies in the outer Solar System, such as faint comets, to explore their mineralogy and hydrocarbon, prebiotic content.

Readers are encouraged to visit the MIRI web site at **http://ircamera.as.arizona.edu/MIRI/** for more information on MIRI science and design. Ω

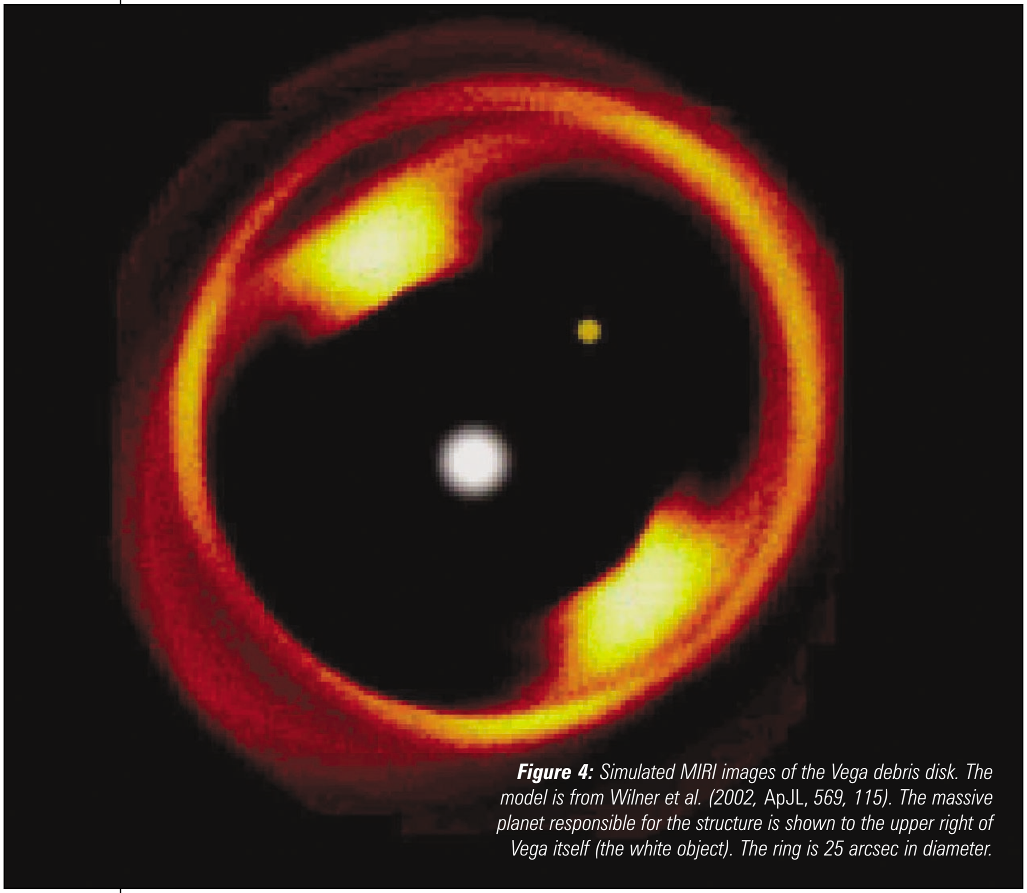

Figure 4: *Simulated MIRI images of the Vega debris disk. The model is from Wilner et al. (2002,* ApJL*, 569, 115). The massive planet responsible for the structure is shown to the upper right of Vega itself (the white object). The ring is 25 arcsec in diameter.*

Hubble Probes the Nature of Activity in Powerful Radio Galaxies

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We now know that quasar activity was about two orders of magnitude more common at redshifts $z \sim 2$ than at the present time. In this context, one of the most important recent developments is the realization that most if not all 'normal' galaxies harbor quiescent black holes (BHs). This raises the question of whether all bright galaxies go through one or more active phases. The duration of an active phase and the time between active phases are unknown.

The tight relationship between BH mass and host galaxy bulge velocity dispersion indicates that the BH mass is 0.1% of the mass of the bulge (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000) and implies that the growth of the black hole and the galaxy bulge are tightly coupled. The growth of the BH may occur in several different ways depending on whether it is mostly due to (1) accretion of other BHs, (2) rapid accretion of gas for short periods of time (about 10 Myr), or (3) slow accretion of gas for the Hubble time. We expect that throughout the process of hierarchical galaxy formation, major mergers and/or gas infall results in both growth of the bulge (star formation) and growth of the black hole (fueling of the active galactic nucleus (AGN)). Thus, these two observable processes—starbursts and AGN activity—could well be directly linked. This raises critical issues concerning the relationship between star formation and AGN fueling. We want to know, for example, over what time scales do these processes occur? Are they short and intense or long and gradual? What is the feedback mechanism that ensures that the BH mass is 0.1% of the mass of the bulge; i.e., that 0.1% of the gas that forms stars is swallowed by the black hole?

Now, for the first time, we can probe the duration of nuclear activity and its duty cycle in individual AGN. Powerful radio galaxies produce extended (up to Mpc-scale) radio sources, which are relatively long lived—typically at least 100 Myr at 1.4 GHz. (Their observability depends on radiative and expansion losses of the relativistic electrons.) There have been anecdotal examples of radio galaxies that showed evidence for multiple epochs of activity (e.g., 3C219, 3C236, 0108+388). Recent radio surveys with the Westerbork Synthesis Radio Telescope (WSRT) and the Very Large Array (VLA) have shown that these sources are not anomalies but represent a class of objects. Now referred to as 'double-double' sources, they constitute about 5 to 10% of predominantly large (> 1 Mpc) radio sources (e.g., Schoenmakers et al. 2000a,b).

The double-doubles show both an outer 'older' radio source and an inner 'younger' radio source propagating outwards amidst the relic of the previous epoch of activity. We think the repetitive activity is due to the fuel supply to the engine being resupplied after having been exhausted or cut off. This general scenario is also consistent with simulations of radio galaxy propagation. We can estimate the relative ages of the inner and outer radio sources and the length of time between epochs of activity using radio observations of the sizes of the sources coupled with a dynamical model for the source and radio spectral energy distributions of the radiating electrons.

In the current paradigm, the radio sources start life as a GHz Peaked Spectrum (GPS) source (size no more than kpc), evolve into a Compact Steep Spectrum (CSS) radio source (size between 1 and 20 kpc), then into a large scale radio galaxy (size greater than 20 kpc). (See O'Dea (1998) for a review of Compact Steep Spectrum and GHz Peaked Spectrum radio sources.) At some point, the nucleus becomes dormant—possibly due to a lack of fuel supply to the central engine, the jets cease, and the previously ejected jet material traverses the length of the source in the light travel time (assuming the jet bulk velocity is relativistic), which shuts off the energy supply to the hot spots. We assume the particles are accelerated primarily in the strong shocks at the end of the jets (perhaps by Fermi acceleration in the Mach disk or MHD turbulence), and we believe that the acceleration will cease when the jet no longer feeds the hot spot. Thus, the particle population will age once the hot spots are no longer fed. If the jet bulk velocity is relativistic, which we believe is true in powerful classical doubles, then the jets will propagate to the end of the radio lobes in about 10 Myr (e.g., in 3C236). The ages of the youngest electrons in the lobe then provide a constraint on the dormancy period of the nucleus.

Recent near-ultraviolet images of the double-double 3C236 provide an important new constraint on the fueling and the nature of the repetitive activity (O'Dea et al 2001). 3C236 is a powerful classical double radio galaxy at relatively low redshift ($z = 0.1$). Its angular size of 40 arcmin corresponds to a linear size of 4 Mpc, making it the largest known radio galaxy and even one of

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the largest known objects in the universe (see Figure 1). The nuclear radio source appears to be a small, classical, double source with an extent of 2 kpc and thus resembles a Compact Steep Spectrum (CSS) radio source.

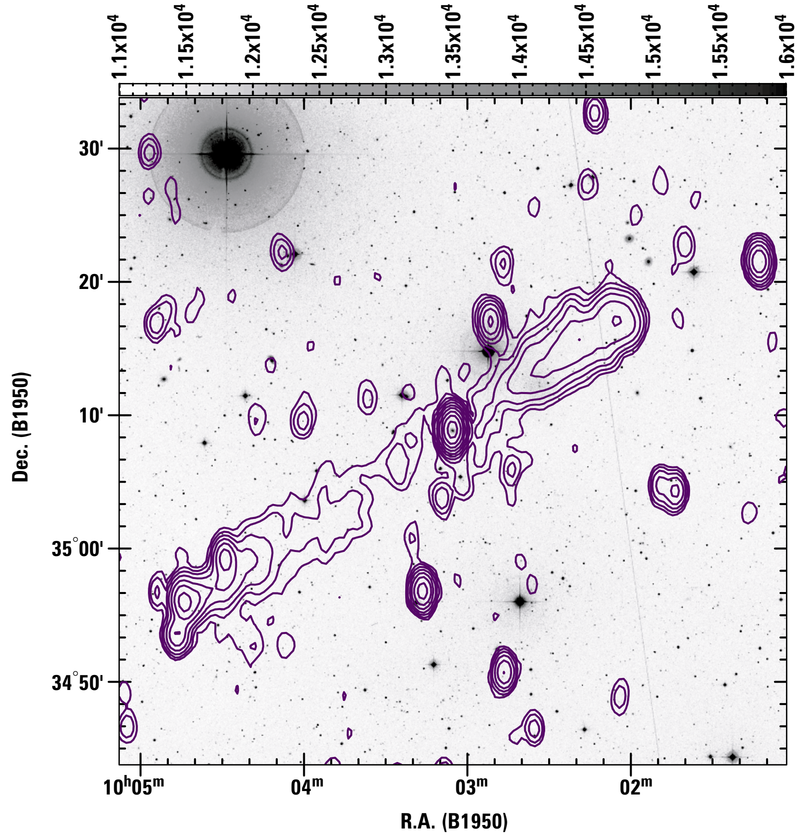

Figure 1: *3C236. Contour plot of 92 cm WSRT image (from Mack et al. 1997) overlaid on the STScI Digitized Sky Survey image. The large-scale radio source has an extent of 40 arcmin, which corresponds to a linear size of 4 Mpc. The resolution of the WSRT image is 55 x 96 arcsec. The contours start at 4.5 mJy/beam (about 3 sigma) and increase logarithmically.*

Using the Multi-Anode Microchannel Array (MAMA) detector on the Space Telescope Imaging Spectrograph (STIS), we have obtained images of the host galaxy in 3C236 and detected four very blue resolved knots on the eastern edge of the dust lane (see Figure 2, opposite page). The knots are located on the edge of the dust lane and are not related to the radio source or to an ionization cone. We believe the knots are regions of recent and/or current star formation.

We have combined our MAMA data with images from the Wide Field Planetary Camera 2 (WFPC2) through the F555W and F702W filters, taken to obtain the colors of the knots. The comparison with population-synthesis models suggests that the colors of the star clusters have a bimodal distribution: (1) the two bluest clusters are consistent with ages of no more than 5 to 10 Myr and metallicities above 20% solar and (2) the redder two of these clusters are consistent with ages ranging up to a maximum of 100 Myr. Thus, although the exact ages are uncertain, we find that the knots span a range in age, with two of the knots being significantly younger than the other two.

The continuing star formation in the disk suggests that gas continues to be transported into the nucleus, thereby fueling the nuclear activity. The bimodal distribution of ages of the starbursts suggests that the transport of gas into the nucleus may be clumpy and sporadic, with different starbursts being triggered by different events of infall/transfer of gas. The existence of non-uniform transport of gas in the disk may be responsible for both (1) the range of ages of the star-forming regions and (2) the apparent episodic nature of the radio source. Ω

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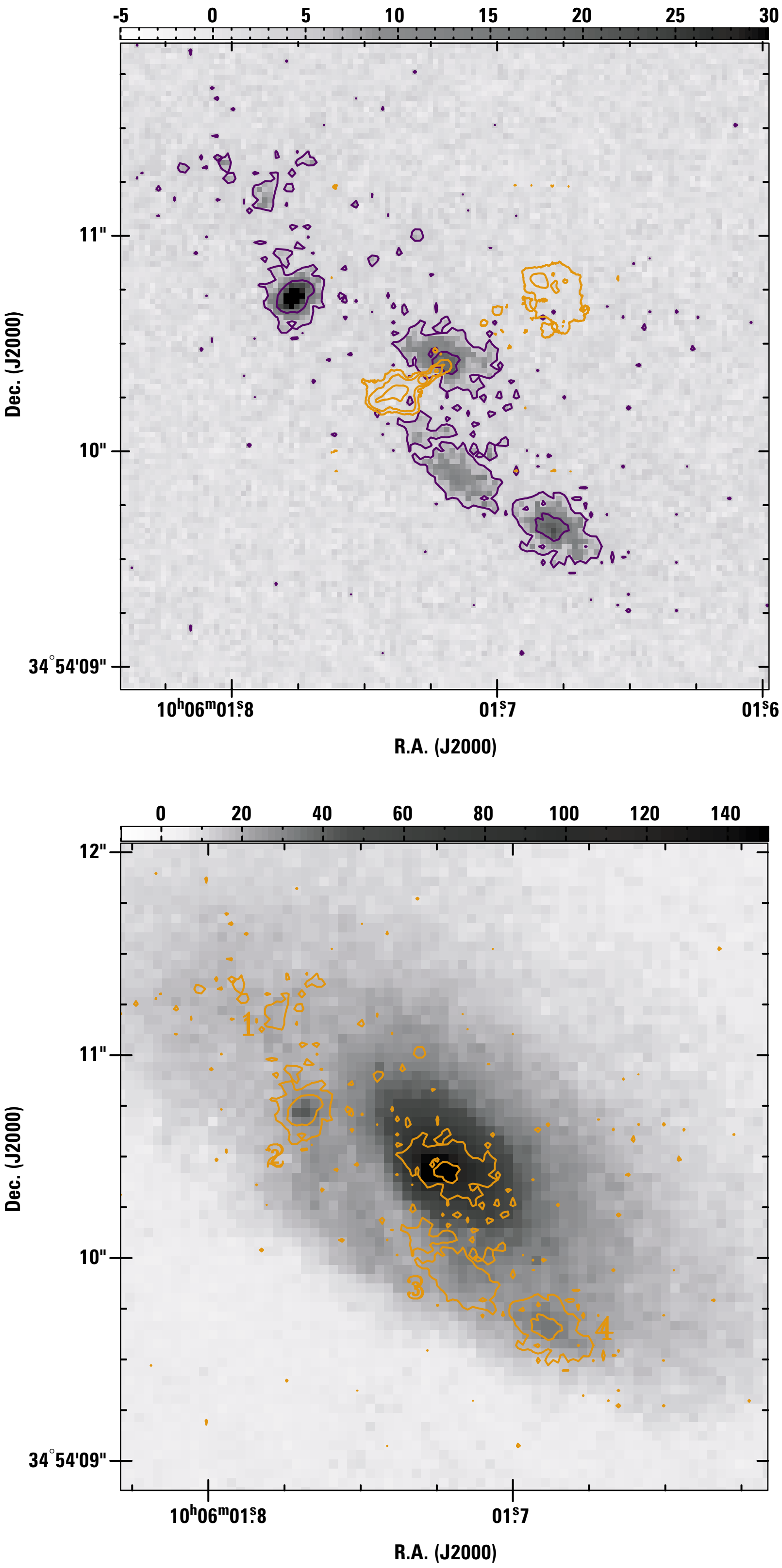

Figure 2: *3C236.* **(Top)** *Overlay of inner 2 kpc radio source (contours) (from Schilizzi et al. 2001) on our STIS UV image (grey scale).* **(Botom)** *Overlay of our STIS UV image (contours) on our WFPC2 F555W V-band image (grey scale) showing the location of the knots along the eastern edge of the dust lane.*

Interview: Sarah Stevens-Rayburn

Sarah, we had no library when you came to the Institute in 1983. Your job was to create it. What were your principle considerations as you designed our library? What were the sources of the books? What issues about the library's size and purposes did you address and decide to shape the library as it is today?

Gosh—ancient history here! I actually started consulting for the Institute in April 1983, while I was finishing up a few things at NRAO (the National Radio Astronomy Observatory), and arrived here on 1 August. There had been a part-time temporary librarian, who had started some subscriptions and taken in a few donations, so when I arrived, there were several dozen boxes of journals (mostly Riccardo's *ApJs*) and books stacked in the corner of this huge empty room. I immediately unpacked them and set them up in rows on the floor while we waited for shelving. It was amusing watching the astronomers scurrying between the rows like crabs looking for stuff. That activity confirmed my suspicion that the first task was to create a working library as quickly as possible. I'd set up one library from scratch already (NRAO's VLA (Very Large Array) in Socorro, New Mexico) so knew how to proceed.

Since launch was a mere two years away (it was a 'mere two years away' for my first decade at the Institute), there was a real urgency to get things accomplished as quickly as possible. I solicited and got a lot of input from the staff about what they wanted, in what format(s), and how far back our holdings should go. They were great at providing input and emptying their own private collections for the overall benefit of their colleagues. Our contract with NASA specified that the purpose was to provide "a library of astronomical, engineering, and other data which is relevant to the ST Program ... in full consideration of other potential sources of that data…". This was interpreted to mean we would have as much of the astronomy material in-house as possible but would depend on Hopkins and Goddard for peripheral stuff. We developed a policy of trying to obtain any material needed by a staff member that we didn't already have.

As to your question about "sources of books," the basic answer is the old saw that it's not what you know but whom you know. My colleagues in astronomy libraries around the world rallied to our aid in supplying long journal runs and publications from their own observatories. We were able to establish exchange relationships with many libraries, which led to wonderful, symbiotic collection building. For example, we had many local offers of more current issues of the *ApJ*, but couldn't find a source for the *MNRAS*. It turned out a library in Poland had lots of *MNs*, but was unable to buy current issues of *ApJ*. Of course we also bought a lot of material from back-issue vendors and through regular acquisitions channels, but much of the really important material came from our friends elsewhere. Once we had established our basic collection, we continued our duplicate exchange so that we could help build new collections elsewhere.

Fire recently destroyed the library at the Mt. Stromlo Observatory. How different will their job be today, to recreate an astronomy research library, than yours was twenty years earlier? I'm wondering particularly if the presence of the Internet will change the design of libraries in the future. How will the Internet change our library?

The real tragedy of the loss of the Mt. Stromlo library is that they had an extensive collection of historical materials, which are simply irreplaceable. For the major journals, of course, there is electronic access and, because they are part of the Australian National University, many more modern materials were duplicated. As usual, the astronomy library community immediately rallied and have offered help in replacing materials that the Mt. Stromlo librarians decide they wish to maintain in paper; i.e., all of the non-journal publications. (In our own library, more than half of the collection is non-journals and none of these are available electronically.)

I think the presence of Internet resources has already changed the face of libraries and will continue to do so, although not necessarily for the better. (See what has turned out to be an oft-quoted article on this topic: " 'If it's not on the Web, it doesn't exist at all': Electronic Information Resources—Myth and Reality," which a colleague and I presented at the LISA III meeting in 1998; **http://www.stsci.edu/stsci/meetings/lisa3/stevens-rayburns.html**).

For instance, I am a member of the Library Advisory Committee for the Optical Society of America. We meet annually to provide information and advice on the directions OSA's publications program (and pricing) ought to take. At these meetings, I hear of more and more institutions that are dropping subscriptions and often removing the print versions of serial titles, depending on the electronic access for their users' needs. Given the extreme uncertainty of archiving of electronic materials, many of these institutions are not trusting the publishers to provide a perpetual archive and are therefore buying and mounting electronic journals in-house. Luckily for us in astronomy, NASA has (so far) decided to underwrite the maintenance of the electronic archive through the Astrophysics Data System. That's the good news. The bad news is that the electronic journals in astronomy make up only about 30% of our collection and most of the remainder is either unavailable electronically (yet) or priced such that we can't afford to pay for access. At the same time, we are facing an ongoing space crunch such that we are quickly approaching the time that for every new volume added, we will have to remove an older one. We will soon have to begin storing—or getting rid of—titles to which we have electronic access. I am postponing that day as long as possible because I still see a surprising amount of foot traffic using materials that are available online. Broadly speaking, we are approaching the time when we will be a 'just in time' library instead of a 'just in case' one, but this is more space- than technology-related. Technology enters the picture because it allows us to reduce the delivery time for the 'just in time' scenario.

You have good occasion to observe Institute staff using the library over long years. Are there categories of users, some more effective or efficient than others? Are there strategies, modes, or 'secrets' of using the library from which many users could benefit?

We do have several categories of users, including those who don't realize they *are* Library users because they sit at their workstations, clicking away on the articles they need, not knowing that the library staff are busily negotiating contracts, arranging access, and paying serious money, all in the background, so that the users don't have to come to the Library. Also, from our beginnings in 1983, we have had an online catalog, so that our holdings can be searched without coming in personally. And we provide the borrower names in the records, so one can retrieve books from colleagues without having to come into the Library. Because the Library is open 24 hours a day, we strive to make it as much a self-service activity as feasible. I even consider it a success when our count of reference questions dips, especially if the hits on our web pages are going up. Unfortunately, we're still getting 150 to 200 questions a month, so we haven't been too successful yet at this! Nonetheless, most of our users are pretty good at finding their way around.

There is a category of users that we refer to as 'high-maintenance.' These are the ones who, despite posted instructions and all sorts of finding aids, *really* want to be walked through the process of finding information, whether it's physically in the Library or out on the web. I am reminded of an engineer years ago at NRAO who told me that a really good librarian was like a ferret—you'd tell her what you needed, and a short time later, she'd appear in your office with the needed document clenched in her teeth! There are still such users, and it is my philosophy that their needs are as important as those of people can find everything on their own. Library service is not a 'one size fits all' undertaking; we do whatever we can to make sure the information needs of our clientele are being met. The most frustrating thing for us is to hear of a user doing without because s/he didn't want to 'bother' us. Trust me: we're here to be bothered!

You ask if there are 'secrets' of using the library, and I really hope there aren't. However, I do have to remind people on an ongoing basis to explore the Library's web pages, starting with the entryway at **http://sesame.stsci.edu/library.html**. The other thing I would encourage users to do is ASK. Our online catalog and the preprint/Hubble bibliography database are extremely powerful and have all sorts of nifty features—but you'd be bored to tears if I described them to you when you weren't interested. What users need to do is feel really comfortable saying to me, "Y'know, it would be really nice if I could do x"—whatever x may be. I or another library staff member can then explain exactly how x is done, and the user has another tool in their toolbox for getting the information s/he needs to do their job. And if x isn't immediately feasible, we'll do what we can to make it so.

You have been a keen observer of the Institute and its cultures over the years. Recently, the Institute has been striving to improve communications and understanding between its diverse parts as well as between individuals of different backgrounds and viewpoints. Do you think we are making progress?

This is an extremely difficult (if not loaded!) question. I can assure anyone who isn't aware that communication in any organization of more than a dozen people is going to be difficult, and it has been difficult here since the Institute's earliest days. I think one of the problems today is that, because of tools like the Internet, we *expect* the information exchange to flow more freely, but it simply doesn't. I think the communications problems fall into two categories. Category 1 is what I alluded to above: if you provide me

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with information when I don't need it, I'm not going to process or hold onto that information, so the time of both of us has been wasted.

Category 2 is being left out of the loop when you ought to have input. For example, if I am supposed to be doing task x, for which I am dependent on tools y and z, and a decision is taken elsewhere in the organization to remove tool y or even to stop funding task x without allowing me input on the decisions, I am going to be a pretty frustrated employee. Another example is when I am spending a portion of my time working on a particular problem and then later discover that others in different divisions are also working this problem. It's fine for two different groups to be tackling a tricky problem. It's not fine if they aren't kept informed of the other's work.

I believe that inroads are being made into these issues and that, to a certain extent, the reorganizations we have experienced over the past few years have attempted to address these issues. The more foundational problem has to do with what we refer to as the culture issue, for lack of more specific language. Our founding documents were clear that the Institute exists because the astronomical community felt that a project as important as Hubble ought to have significant input and control by those who stood to 'gain' the most from it—the astronomers and other scientists, who would be able to push the envelope of humankind's quest for knowledge. In the early days of the Institute, this was extraordinarily clear to almost all employees. Each task contributed to the whole in a significant way, and we were all excited by being part of this great experiment. The computer scientists and the engineers worked with the astronomers with a single focus—to make Hubble the most productive and useful tool possible. Somewhere along the line, however, the single focus got blurred and individual working groups moved from trying to make Hubble the best possible to trying to make their specific group's task the best possible. This is not necessarily a bad secondary goal, but it often came to overshadow the primary goal. This was an extremely subtle transition, and the result has been, to a certain extent, a kind of isolation—a tendency to say, "I know what's best and you'll just have to accept that." Groups developed a kind of professional elitism that resulted in their feeling misunderstood by the other groups and underappreciated by them.

I believe management has come to be aware of these issues and is putting energy into coping with them, but it is not a simple process. It requires commitment from the heart and not just the head, along with demonstrated zero tolerance of attempts to inappropriately pull rank or to be dismissive of the contributions of those doing less visible tasks. The fact that these topics are being talked about in various forums is a huge step forward and needs to be continued. These aren't problems to be 'solved' but rather behavioral attitudes to be realigned and corrected. Change won't come suddenly, but it *can* come if we remember our mandate to be one team serving the astronomical community.

You and your husband Don have long volunteered your time to Habitat for Humanity, to create good homes for people who are less fortunate. Can you tell us something about this movement and what drew you to it? If others on the staff wished to get involved, how would they do so?

Don and I have been infected with a non-fatal disease known as 'Infectious Habitatis' for the past decade. The visible symptoms are spending almost all of our Saturdays working with other volunteers at Sandtown Habitat for Humanity in west Baltimore and incredible joy in being able to give back a little to the city that has welcomed and nurtured us for 20 years. Our church has sponsored (that is, provided funding and volunteers) for eleven houses so far and will be starting on house number twelve in May. Don and I have worked on these and dozens of others sponsored by different churches and businesses. Unlike most Habitat affiliates—there are some 1900 affiliates in 83 countries—who do new construction, we take 100-year-old rowhouses and convert them into simple decent homes, working in partnership with Habitat staff, neighborhood homeowners and perspective homeowners, and other volunteers. The homes are sold at no profit to individuals or families who have contributed hundreds of hours of 'sweat equity'. The purchases are financed with affordable, no-interest loans, and often the mortgage payments are less than what families have been paying in rent to absentee landlords for substandard housing. The mortgage income is then used to finance more Habitat houses. Information about Habitat International can be found at **http://www.habitat.org/how/factsheet.html**. Locally, there are two Baltimore City Habitat chapters: Sandtown Habitat, with whom we have been working (**http://www.sandtownhabitat.org**), and Chesapeake Habitat, which works in the Waverly/Pen Lucy area of town (**http://chesapeakehfh.org/**). Both chapters welcome volunteers (and donations), and there are tasks for every skill level imaginable. And of course, I am always happy to give interested folks additional information or the opportunity to join us some Saturday in Sandtown! Ω

Hubble Gets Started

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Dr. Roman was Chief of the Astronomy and Relativity Programs in the Office of Space Science at NASA from 1960 until her retirement in 1979. This essay is excerpted from Exploring the Universe Vol. V: Exploring the Cosmos (NASA SP-2001-4407), John Logsdon, Editor, National Aeronautics and Space Administration, NASA History Office, Office of Policy and Plans, Washington DC, 2001, p. 501 ff.

Even before NASA was created, astronomers had dreamed seriously of a large space telescope.[1] As early as 1962, a Space Studies Board (SSB) summer study suggested that it was time to start planning of such an instrument.[2] This was an exciting possibility, and not only for the astronomers. NASA's Langley Research Center started a study of the project, with a human along as an observer. Several aerospace companies, partly funded by NASA, began studies of how such a telescope might be launched and controlled.[3] Aden Meinel, an early proponent of a large space telescope, started a Space Division at the Kitt Peak National Observatory even before the start of the Apollo program. He was a major proponent of the telescope at both the 1962 and 1965 SSB meetings.

Not all astronomers were enthusiastic about the project. To quote Meinel, "Ira Bowen [the director of the Mount Wilson and Palomar Observatories] said at one meeting that one could never stabilize a space telescope enough to yield high resolution. He said that simply pulling out the dark slide would disturb it. He also remarked that higher [angular] resolution wouldn't be of much importance to astrophysics."[4]

In spite of the strong division of opinion about a large space telescope, by the 1965 SSB summer study, momentum behind the project had grown to the point that NASA Headquarters decided that it was important to start planning for the mission.

Various additional studies were funded to prove the feasibility of the idea and to investigate the areas thought most likely to require extensive development. A committee of the SSB, under the chairmanship of Lyman Spitzer, began a four-year activity to define the scientific uses of a large space telescope.[5] The Astronomy Program in NASA Headquarters and astronomers on the Astronomy Working Group (an advisory committee that was composed of astronomers from both NASA centers and the non-NASA astronomy community) began to develop the arguments for such an instrument.

In 1970, NASA established two committees: an LST[6] Task Group to map out the engineering requirements of the project, and a Scientific Advisory Committee to define the scientific requirements. NASA Headquarters officials chaired both committees. The Task Group was primarily an in-house committee from NASA centers; the Advisory Group had a primarily, but not exclusively, non-NASA membership.

In 1971 and early 1972, Goddard Space Flight Center and Marshall Space Flight Center conducted competitive Phase A (preliminary) studies of the LST. However, when it came to deciding how to partition work between the centers, the decision was based primarily on the fact that Goddard already was fully involved with other science projects, while Marshall, whose work was declining after the push for Apollo, was anxious for a new responsibility. Hence, the overall management of the project was assigned to Marshall in 1972. Nevertheless, Goddard, with its experience in astronomy, retained the management of the scientific instruments. At the urging of the scientific community, C. Robert O'Dell was brought to Marshall as the project scientist. Because Marshall would be managing the project, the Science Advisory Group was transferred to Marshall under O'Dell's leadership. Typical instruments were defined, and various groups were selected to work with the project to ensure that the spacecraft could accommodate such instruments. At about the same time, it was decided that the project should be divided into three sections: the Support Systems Module, the Optical Telescope Assembly, and the Scientific Instruments, each to be contracted for separately. This made the management of the project particularly complex.

> **"To quote Meinel, 'Ira Bowen said at one meeting that one could never stabilize a space telescope enough to yield high resolution.' "**

In early 1973, politically astute NASA managers realized that the cost of the LST would limit their ability to sell it to either the Administration or Congress. Hence, Marshall was given a cost target well below its estimate of the cost of the telescope concept then under examination. Various cuts were made in the plans to reduce the cost; these reductions often had to be reinstated later in the program. The flight of a precursor 1.5-meter telescope to test the many complicated systems on the LST was dropped at this time.

In 1974, Congress appeared unenthusiastic about the LST. The House cut all funds for the project. At this point a few astronomers, primarily in Princeton, rallied their colleagues nationwide to lobby for the LST. A major argument made by skeptical Congressmen was that the National Academy of Science's study of astronomy in the 1970s barely mentioned the LST. This was partly the case because the study's chairman, Jesse Greenstein—perhaps because he had been burned almost three decades earlier by his V-2 experience and also because of his West-coast connections—was unenthusiastic about the large space telescope idea. More importantly, the study committee doubted that the telescope could be launched before 1980, thus falling outside the range of the committee's responsibility. By this time, the Academy had embarked on a new study that was to elevate

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[1] **Lyman Spitzer,** in Lyman Spitzer and Jeremiah P. Ostriker, eds., *Dreams, Stars, and Electrons,* p. 369, with reference to H. Oberth, *Die Rakete zu den Planetenraunien* (Munich, Germany: R. Oldenbourg Verlag, 1923). Spitzer actually credited German rocket scientist Herman Oberth for suggesting a space telescope in 1923.

[2] **Space Science Board,** *A Review of Space Research* (Washington, DC: National Academy of Sciences, 1962).

[3] **The Boeing Company,** "A System Study of a Manned Orbital Telescope."

[4] **Aden Meinel,** personal communication.

[5] **Space Science Board,** *Scientific Uses of the Large Space Telescope* (Washington, DC: National Academy of Sciences, 1969).

[6] Although LST stood for Large Space Telescope, in the minds of many astronomers it also stood for the Lyman Spitzer Telescope, given Spitzer's seminal role in proposing the concept.

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the LST to top priority, but this study had not yet been completed. To counteract the impact of the Greenstein report, the study committee was again polled for its views on the LST. This time, after additional lobbying within the astronomical community, the Academy committee unanimously gave the LST top priority. Influenced by this result and extensive lobbying, the Senate was convinced to include the requested funding. As often happens, the House-Senate conference committee split the difference; NASA received half of the amount that had been requested.

Congress agreed to supply additional funds for the project only if significant foreign involvement in the LST was included; this would decrease the cost of the project to the United States. After extensive negotiations between NASA and the European Space Research Organization (ESRO; later succeeded by ESA), Europe agreed to supply a major scientific instrument and the solar arrays. In return, European astronomers were guaranteed 15 percent of the observing time. Although both the decision to accept a European instrument without competition and the guarantee of observing time upset some U.S. members of the study teams, it was likely that the Europeans could have successfully bid for 15 percent of the observing time in any open competition. Moreover, it was unlikely that NASA would have been able to fund an additional instrument, or even get Congressional approval for the LST overall without the European contribution.

In October 1975, President Gerald Ford cut the federal budget by $28 billion in order to try to balance the budget in three years. The NASA response to its share of the cut was to drop the new start for the LST in the Fiscal Year (FY) 1977 budget request. The Office of Management and Budget also felt that because of a slip in the Shuttle schedule, FY 1977 was too early to start LST, and James Fletcher, the Administrator of NASA, believed that the new start was politically unfeasible. Instead, NASA requested a new start for the Solar Maximum Mission in FY 1977 and no funds specifically for the LST. Again the astronomical community launched a major lobbying effort, both in Congress and with NASA. The NASA administrator then argued for support of the LST with President Ford. The result was that a new start for the project slipped to FY 1978. The "L" was dropped in references to the project-making it just "ST"—so as not to advertise its cost, although some astronomers were concerned that the name change was an indication that the project's scope might be cut further.

> **"...for the price of a night at the movies, the average American could enjoy fifteen years of exciting discoveries."**

At about this time, Senator Proxmire asked NASA why the average American taxpayer should want to pay for such an expensive project. NASA's answer was that for the price of a night at the movies, the average American could enjoy fifteen years of exciting discoveries. Although it is unlikely that this response made any difference, it is interesting that as both the ST and movies have increased in cost, the statement is still approximately true.

NASA Headquarters directed the Marshall Space Flight Center to find ways to cut the cost of the project in preparation for a FY 1978 new start. Marshall suggested various ways, of which the most draconian was to decrease the size of the telescope's mirror. The original plan called for a three-meter mirror. Both contractors and scientists were asked to look at the impact of including a mirror in each of three sizes: 3, 2.4, and 1.8 meters.

A major objective of the ST was to improve knowledge of the Hubble constant. This is the ratio between the speed of recession of a galaxy and its distance. The Milky Way is a member of a group of thirty to fifty galaxies that interact gravitationally. Thus their motions are affected by this gravitational interaction in addition to the expansion of the universe. To measure the Hubble constant, it is necessary to determine the distances of galaxies outside this Local Group. The most significant collection of the nearest such galaxies lie in the Virgo cluster. Thus, it had been assumed from the beginning that the LST must be able to observe Cepheid variable stars in the Virgo cluster. It had been known for most of a century that the period of the variation of a Cepheid is closely correlated with its intrinsic brightness. Hence, to measure its distance, it is only necessary to measure the period of the variation and the mean or maximum brightness. The astronomers determined that a 2.4-meter telescope could still obtain these measurements; a 1.8-meter telescope could not. Therefore the astronomers on the Science Advisory Group agreed that they could accept a 2.4-meter objective, but that they would recommend that the project be ended rather than settle for a 1.8-meter mirror.

Also, facilities existed for the manufacture of a precise 2.4-meter mirror, while new facilities would have to be built for a three-meter mirror. This would greatly increase the cost of the Optical Telescope Assembly. Reducing the mirror size to 2.4 meters would also relax the pointing requirements and simplify the pointing and control system. Moreover, using a 2.4-meter mirror would simplify the control design even more by allowing the designers to wrap the heavy Support Systems Module around the telescope.

By the time the FY 1978 budget was ready to go to Congress, NASA had gotten both the President and the Office of Management and Budget enthusiastic about the project. Moreover, after several years of experience, the astronomers had become more skillful and sophisticated lobbyists.

A new start for the ST was approved at last in the President's FY 1978 budget proposal. Technical problems now came to the fore. Because of stringent restrictions on overall NASA personnel as well as on the project's budget, and because Marshall had a reputation of excessively enlarging project personnel, Marshall was given a very stringent personnel cap for the telescope project. With far too few capable people, Marshall had to manage two associate contractors, an international partner, and another center, each of which was in turn dealing with a number of subcontractors. Partly for this reason and probably because of the reluctance of the national security community to allow "outsiders" full access to those portions of the project with a national security heritage, NASA was unable to monitor its contractors closely. Also, relations between Marshall and Goddard were severely strained for the first few years of the project.

Almost immediately after the Phase C/D (development, construction, and preparation for launch) contracts were awarded, each of the contractors increased their cost estimates substantially. Yet, Marshall was not allowed to budget for any additional funds. These factors led to a continuing series of severe problems until NASA Headquarters stepped in in a major way in 1983. Project managers were replaced at both Marshall and Goddard. The new managers made a determined effort to work together, thus solving one problem. Also, NASA Headquarters, after careful review of the project, agreed that substantially more money and manpower should be allotted. Although, as in any complex technological project, there were many problems after this, they were under more control. There were also schedule slips, but a launch in late 1986 still seemed possible. The 1986 *Challenger* accident eased the schedule problem, but also substantially increased the cost of the program as the spacecraft remained in storage in a clean room in Palo Alto, California, for three years, while the project team had to be kept together until the launch.

As the Ramsey Committee had stated in the 1960s, university astronomers wanted a non-NASA institute to manage the science of the project. In contrast, astronomers at NASA's Goddard center were anxious to have scientific control of the project. This led to a major fight, which the university-based astronomers won. In addition to granting the wish of the scientific community, NASA Headquarters recognized that the size of the necessary institute would overwhelm Goddard, and particularly its small astronomical staff. The Space Telescope Science Institute (STScI) got off to a rocky start in its relations with NASA. Riccardo Giacconi, the director selected, had ambitious plans for the STScI, and immediately indicated that the staff had to grow significantly above that described in the proposal. Just as NASA Headquarters officials had failed to respond to the sometimes desperate requests for funds from Marshall, they also tried to squelch the staffing and budget growth demanded by the STScI. Finally, after a careful look at the functions for which NASA believed the STScI should be responsible, some of which had not been included in the original specifications, NASA agreed to a major increase in personnel and space. Over time, the relations between Giacconi and NASA became smoother, with each developing a better understanding of the other's problems. Ω

Dr. Roman currently works with fifth and sixth grade classes for several sessions each semester. She had based the session pictured here, Mr. Leonard's fifth grade class at Shepherd School in Washington, DC, on time, having the students make star clocks and plan the packing list for a trip to their favorite planet.

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