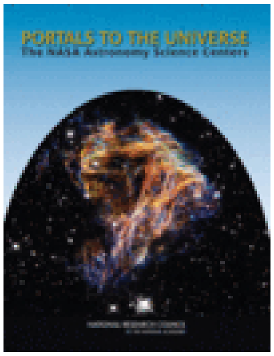

Portals to the Universe: The NASA Astronomy Science Centers

Committee on NASA Astronomy Science Centers, National Research Council

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PORTALS TO THE UNIVERSE
The NASA Astronomy Science Centers

Committee on NASA Astronomy Science Centers

Space Studies Board

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Preface

The field of astronomy and astrophysics has advanced significantly with the advent of orbiting observatories. The ability to observe unobstructed by Earth's atmosphere has opened new spectral windows and provided clearer, deeper views of the universe. Working with powerful new ground-based tools, astronomers and astrophysicists have revolutionized our understanding of the universe and the physical laws that govern its existence.

In the United States, the National Aeronautics and Space Administration (NASA) has built, operated, and supported researchers using a wide variety of space astronomy missions, from the famous Hubble Space Telescope to small missions like the Swift mission. NASA has founded a number of astronomy science centers (distinct from its field centers) that serve as interfaces between the spacecraft and the research community. These science centers vary in size and responsibility, depending on the mission that they are tasked to support.

With NASA's success and the consequent growth in the number of science centers associated with astronomical missions, and in the light of several planned space astronomy missions and the need to consider centers to support those missions, NASA requested that the National Research Council conduct a study to carry out the following tasks:

- Conduct a comparative review of current astronomy science centers in terms of the kinds of roles and services that they provide; their size, for example, their budget and staff; the extent to which they utilize centralized or distributed approaches to their architecture; the roles and status of their staff; the nature of their host or governing institution and their governance structure; and how the centers were established by NASA—that is, by sole source or competitive procurement.
- Identify best practices and lessons learned from experience to date with NASA astronomy science centers.
- Assess whether there are optimum sizes or approaches for science centers, whether there are rational break points in levels of service for the centers, and what may be the main advantages or disadvantages of different scales of service.

Early in the study process, the committee learned of budget cuts to NASA's astronomy and astrophysics program. Several missions in the planning stages were expected to be delayed for the foreseeable future. With that information, the committee decided to focus on the existing centers as examples of the ranges and sizes of science centers in order to determine whether new approaches to astronomy science centers would be necessary in the near future. In any case, it was not the purpose of this study to assess the performance of the science centers. Rather, the comparison of existing centers and the lessons learned from experience form the basis for inferring best practices and optimum sizes and approaches.

The statement of task for the study (Appendix B) cited six astronomy science centers—the Space Telescope Science Institute, the Chandra X-ray Center, the Spitzer Science Center, the Michelson Science Center, the X-ray Multimirror Mission–Newton guest observer facility, and the Rossi X-ray Timing Explorer mission guest observer facility—and the committee's work for this report focused on these centers. Accordingly, the committee (see Appendix C for members' biographies) obtained written information and heard presentations from the leaders of the science centers and assembled panels of experts, from research scientists to high school science teachers. Such a review will inform the committee on the full range of center services. The chair of the committee also visited each of the science centers discussed in the report as well as two archival centers, the High Energy Astrophysics Science Archive Research Center at NASA Goddard Space Flight Center and the Infrared Processing and Analysis Center at the California Institute of Technology. In this report the committee describes the functions and responsibilities of an astronomy science center, models of science centers for missions of various sizes, and the principles that should guide the establishment, operation, and evolution of science centers, and it makes recommendations for the future of NASA science centers.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Robert Chen, Center for International Earth Sciences Information Network,
Brian Drayton, TERC,
Neal J. Evans, University of Texas at Austin,
Sarah Gallagher, University of California, Los Angeles,
Walter Gekelman, University of California, Los Angeles,
Peter Quinn, University of Western Australia, and
Burton Richter, Stanford Linear Accelerator Center.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Stephan Meyer, Enrico Fermi Institute, University of Chicago. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

The astronomy science centers established by the National Aeronautics and Space Administration (NASA) to serve as the interfaces between astronomy missions and the community of scientists who utilize the data have been enormously successful in enabling space-based astronomy missions to achieve their scientific potential. These centers have transformed the conduct of much of astronomical research, established a new paradigm for the use of large astronomical facilities, and advanced the science far beyond what would have been possible without them.

PURPOSE OF THE STUDY

NASA astronomy science centers take a number of forms and have been compared in terms of many factors, including cost, personnel, services offered, and the size of the community served (see Chapter 3 and Appendix A, Table A.1). The centers enable continuing scientific and educational use of the data during the operational life of a space-based astronomy mission and for years afterward. When NASA considers establishing new observing facilities, its decision on whether to use existing science centers, create new ones, or pursue other vehicles for data archiving, education and outreach, and community support for that mission is often critical. To that end, NASA asked the National Research Council (NRC) to examine current astronomy science centers with respect to their roles and services, to identify lessons learned and best practices, and to consider whether there are optimum sizes or approaches for such centers (see Appendix B for the study charge).

NASA ASTRONOMY SCIENCE CENTERS AND THEIR FUNCTIONS

NASA empowers a range of center types and sizes, from relatively modest facilities to large, full-service science centers, with budgets ranging from approximately $6 million to $80 million (Appendix A). As requested in the study charge, the committee examined a cross section of center types, including a small mission center, the Rossi X-ray Timing Explorer (RXTE) guest observer facility (GOF); a guest observer facility, the X-ray Multimirror Mission–Newton (XMM–Newton); three larger flagship mission science centers, the Space Telescope Science Institute (STScI), the Chandra X-ray Center (CXC), and the Spitzer Science Center (SSC); and a center focusing on interferometric data, the Michelson Science Center (MSC). The committee also considered two archival centers: the High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA's Goddard Space Flight Center (GSFC) and the Infrared Processing and Analysis Center (IPAC) at the California Institute of Technology (Caltech). It discerned a consistent set of functions and services that allow the research community to utilize the data in creative ways that advance research and our understanding of the cosmos and to preserve the data and metadata for future use, including the following:

- Support of flight operations,
- Instrument support and calibration,
- Data analysis and Level 1 processing,
- Archiving and distribution of data to the research community,
- Software development and documentation for science analysis,
- Help desk and other user support services,
- User workshops and symposia,
- Proposal submission processing and peer review evaluation,
- Grant management and administration,
- Scientific research,
- Advocacy and strategic planning, and
- Education and public outreach.

The committee's assessment identified the factors that impeded or aided a center's ability to provide the full range of these functions effectively.

FINDINGS AND RECOMMENDATIONS

NASA Astronomy Science Centers for Managing Current and Planned Missions

The committee concluded that the core services of astronomy centers—mission support, scientific research, and data archiving—could be viewed as reaching their fullest performance at the following astronomy centers: (1) STScI, (2) CXC, (3) HEASARC and its associated RXTE and XMM–Newton guest observer facilities, and (4) IPAC and its associated Spitzer and Michelson science centers. The committee concluded that because a number of space-based astronomy missions had been delayed, the existing astronomy centers have sufficient scientific and programmatic expertise to manage all of NASA's astronomy center responsibilities now, for the foreseeable future, and after the active phases of current and planned missions have been completed.

Finding: The Chandra X-ray Center, the Space Telescope Science Institute, the High Energy Astrophysics Science Archive Research Center, and the Infrared Processing and Analysis Center have sufficient scientific and programmatic expertise to manage NASA's current science center responsibilities after the active phases of all current and planned space-based astronomy missions have been completed.

Recommendation 1. NASA should establish a large new center only when the following criteria

are met: (1) the existing centers lack the capacity to support a major new scientific initiative and (2) there is an imminent need to develop a new infrastructure to support a broad base of users.

The committee viewed the presence of research scientists and visiting scientists at the NASA astronomy science centers as enhancing the role of those centers and their ability to provide exciting and intellectually rich environments for the research scientists they employ. No additional full-time researchers are required for a center to serve the community effectively, and the committee believes that all scientists at a center should be involved, at some level, in facilitating the mission with which the center is involved.

Finding: The ability of the Chandra X-ray Center, the Space Telescope Science Institute, the High Energy Astrophysics Science Archive Research Center, and the Infrared Processing and Analysis Center to provide the appropriate level of support to the scientific community depends critically on the extent to which they can attract, retain, and effectively deploy individuals with the mix of research and engineering skills necessary to maintain continuity of service.

Guest Observer Facilities and Explorer-Class Mission Centers

It was clear to the committee that all of the NASA astronomy science centers examined for the study can provide valuable services to the community, but that the smaller GOF and Explorer mission centers lack the resources and staff support to provide the full range of science center services effectively on their own. GOFs such as those for RXTE and XMM–Newton can manage a modest level of service in many areas only because they are able to draw on portions of the time of talented people who were engaged in other activities at their institutions. Associating GOFs or Explorer centers with the larger archival centers or flagship mission centers, which have staff and infrastructure in place, enables them to leverage necessary skills and services and serve their scientific constituents.

Finding: Embedding GOFs in existing science centers, such as the HEASARC, provides for efficient user support, especially when the scope of a space mission does not require establishing a separate center.

The archival centers provide an important service insofar as they are able to accommodate mission centers at varying stages of operation and to move staff among projects as missions start up or wind down. The sharing of staff scientists among center missions and the transitioning of staff as missions start and end provide both stability and flexibility. The archival centers also provide proposal and analysis software, search tools, and other resources that users can apply to the multiple databases they hold. Further benefits accrue in the knowledge base that staff acquire from one mission to the next, which allows for transferring best practices and lessons learned among missions.

BEST PRACTICES FOR ASTRONOMY SCIENCE CENTERS

The committee identified a set of best practices for the flagship and archival NASA astronomy science centers that, if adopted, can guide their continued effectiveness (Box S.1). Should the opportunity arise and the conditions be met for establishing a new center, the best practices can serve as input to selecting operational functions for it.

BOX S.1 Best Practices for NASA Astronomy Science Centers

Mission Operations

NASA astronomy science centers can best operate the spacecraft and process the resulting data if they

- Have close interaction among scientists, engineers, and programmers. Such interaction is especially important for off-site principal investigator (PI) teams.
- Have research scientists who participate actively in mission operations and in policy decisions.
- Have mission staff knowledgeable about the instrumentation and the satellite in order to provide detailed advice and technical support to the user.
- Provide adequate instrument calibration.
- Provide functional software by the time data first arrive.

Science Operations

NASA astronomy science centers can best support their scientific user communities if they

- Support robust, accessible, well-documented software.
- Use common rather than instrument-specific software across missions when possible.
- Maintain adequate online supporting materials and a help desk with adequate staffing and rapid turnaround.
- Provide user-friendly protocols and software for proposal entry and require minimal technical details for the initial proposal.
- Enable coordinated observations and proposal submission among multiple space- and/or ground-based observatories.
- Co-locate staff to support multiple missions with related scientific objectives.
- Retain key science center staff by providing them with evolving opportunities in either multiple missions or within the host/managing institution.

Recommendation 2. NASA should adopt a set of best practices as guiding principles to ensure the effectiveness of existing flagship and archival NASA astronomy science centers and to select the operational functions of any future centers.

COOPERATION AMONG SCIENCE CENTERS AND AGENCIES

Cooperation among NASA astronomy science centers and related agencies can lead to a greater impact on research results, data access, and educational activities. For example, researchers may be able to cross discipline and wavelength boundaries in analyzing astronomical data. Providing tools and formats that are common to all wavelength bands and supporting common protocols and formats for proposal entry can facilitate multiwavelength research. The committee concluded that astronomy sci-

- Give scientists at science centers guaranteed research time but not guaranteed observation time.
- Have a visiting scientist program.

Data and Archiving

Science centers can best process, store, and disseminate their data if they

- Provide rapid (<24 hr) response to requests for data that have been calibrated and archived.
- Support common analysis software and protocols that can be used by all the science centers.
- Maintain mission expertise at the archive centers for the long-term support of active users.
- Ensure that standards for access to all astronomical data archives are coordinated by an entity such as the National Virtual Observatory and that the infrastructure, including formats and analysis tools, is accessible and sustainable.

Education and Public Outreach

Science centers can best communicate their results to the public if they

- Involve staff scientists and investigators in education and public outreach (EPO) activities.
- Coordinate EPO efforts of smaller missions with EPO systems of the large NASA astronomy science centers.
- Develop classroom resources that
  — Are designed iteratively through field testing and evaluation in actual classrooms.
  — Include hands-on activities when possible.
  — Support standards-based curricula.
  — Are packaged with protocols for measuring learning effectiveness.
  — Are accessible and cross-linked so that teachers can easily find them.
  — Include teacher support (e.g., Web-based teacher guides, training for master teachers).

ence centers need to develop a coherent strategy for K-12 education if their educational activities are to have a greater impact.

Recommendation 3. NASA should ensure that NASA astronomy science centers cooperate among themselves and with other agencies to develop strategies and plans for

- **Developing common protocols and formats for proposal entry;**
- **Developing a universal infrastructure for data formats and metadata, archiving, and retrieval and analysis tools; and**
- **Providing curriculum materials and professional development programs for K-12 teachers.**

1

Introduction

The astronomy science centers[1] established by NASA to serve as interfaces between astronomy missions and the community of scientists who utilize the data from those missions have been enormously successful in enabling space-based telescopes to achieve their scientific potential. As described below, NASA science centers have transformed the conduct of much of astronomical research and set in place a new paradigm for the use of all large astronomical facilities. It is against this background of success that the committee that wrote this report had been charged by NASA with comparing the approaches taken by the science centers to the requirements they faced, drawing on experience for best practices from their experience, and making recommendations for future science centers.

The NASA astronomy science centers perform a number of essential functions for the research community. It is through the centers that most scientists get to use the space-based telescopes. The centers construct the observing programs of the satellite/telescopes. Data gathered by the telescopes pass through the centers to the scientific community via an archive that preserves the data for future research. The centers construct and maintain the software necessary to carry out the preceding functions as well as the vital software for data reduction. They have taken over what was traditionally the NASA Headquarters role—namely, announcing opportunities for proposal submission and conducting proposal review, ranking, and award of observing time. NASA financial support to mission users in the form of data analysis grants typically, though not necessarily, passes through the science centers. The centers also interface with the public and conduct programs in science education and public affairs.

[1]In this report, unless noted otherwise, "center" refers to an astronomy science center associated with a NASA astronomy mission, such as the Space Telescope Science Institute (STScI) or the Chandra X-ray Center (CXC), not to a NASA field center, such as NASA's Goddard Space Flight Center (GSFC) or Marshall Space Flight Center (MSFC). In addition, the committee views astronomy science centers as including stand-alone centers such as the Space Telescope Science Institute as well as archival science centers, such as the Infrared Processing and Analysis Center (IPAC) and the High Energy Astrophysics Science Archive Research Center (HEASARC), which are umbrella institutions for certain mission-oriented science centers.

EXPANDING ACCESS TO SPACE ASTRONOMY DATA

The early years of the space program were dominated by entrepreneurs who developed instruments for inclusion in rocket payloads and then on satellites. The data from those experiments belonged to the entrepreneurs, so there was no requirement to invest resources into making the data usable by other researchers. New data formats were invented for each new set of observations, and it was impossible for researchers to use the data without the expert assistance of the primary investigators. Although the data were formally deposited in NASA's National Space Science Data Center (NSSDC), the archive was effectively inaccessible without an invitation to visit the home institution of the principal investigator (PI).

NASA and the astronomy community took several steps to remedy what had become an insular culture for accessing space astronomy data by expanding the number of users and increasing the use of the data. These steps included but were not limited to (1) the introduction of a new institutional model for NASA astronomy science centers, as exemplified by the STScI; (2) informal and formal measures to provide access to archival data from space astronomy missions; (3) NASA requirements to expand use of space astronomy observatories through guest-observer programs; (4) standardization of data formats; and (5) expansion of the role and functions of astronomy science centers to include proposal reviews and education and outreach.

An Institutional Arrangement for NASA Astronomy Science Centers

A milestone in the emergence of NASA astronomy science centers was reached with the planning in the early 1970s for the Large Space Telescope, renamed the Hubble Space Telescope (HST) after launch. A mission of this scale clearly had to be considered a national if not an international resource, and NASA and the astronomy community were anxious to engage a larger fraction of the community as users of the data. To do this, the Hornig Committee[2] was chartered to "undertake a study of the possible institutional arrangements for the use of the ST [Space Telescope]."[3] The Hornig Committee report, released in 1976, recommended the creation of an independent, nongovernmental institution for archiving the data and supporting the telescope users. Although the report was meant to be published just in time to provide a scientific management model for the Hubble Space Telescope, the spacecraft was not launched until 14 years later.

At the same time, during the late 1970s, NASA had also become aware that a larger community of scientists was eager to participate in the entire enterprise of space astronomy. In response to this growing community interest, mission groups such as the International Ultraviolet Explorer (IUE) and the Einstein Observatory, which were operating at the time, took steps to increase access to the data. The IUE, launched in January 1978 and operated out of the Goddard Space Flight Center (GSFC) and the Vilspa satellite-tracking center in Villafranca, Spain, was essentially an all-guest-investigator facility that was modeled on a typical ground-based mountain observatory. Investigators went to Goddard or Vilspa and gave first-hand instructions to a satellite operator for their observations. They could immediately access first-level processed data to utilize simple analysis programs and to develop their own specialized analysis software. IUE operated in this mode for 18 years, servicing astronomers capable of "going to the mountain" to do their observations and of developing their own software for detailed analysis. In addition, the Einstein Observatory, launched in 1978 as the first true x-ray observatory, represented a revolution-

[2]National Research Council, 1976, *Institutional Arrangements for the Space Telescope—Report of a Study at Woods Hole, Massachusetts,* July 19-30.

[3]Ibid., p. iv.

ary increase in x-ray astronomical capability and was an important step forward in the manner in which nonexperts could access data from NASA missions. As in the case of IUE, guests could plan observations, although the preparation of the detailed Einstein observational program required the assistance of specialists. Unlike IUE, which recorded the spectra of individual objects, the Einstein Observatory made x-ray images of the sky. Guests were provided with extensive data analysis support by members of the Einstein team, with the standard scenario involving a weeklong visit to the Einstein Center at the Harvard-Smithsonian Center for Astrophysics in order to learn how to utilize the data and the analysis software. The imaging data lent themselves to large archival survey studies, which were conducted almost exclusively by the members of the Einstein team, who could easily access the data and develop the necessary software. Although the data format was unique to the Einstein mission and the analysis software was not easily exported or externally maintained, the processed Einstein Observatory imaging data were made available for archival research to an extent not previously achieved for astronomical data from space. The availability of archival data expanded the range of users of IUE and Einstein data to include non-x-ray astronomers who sought to augment their understanding of astronomical objects by analyzing x-ray observations of the same objects.

Finding: The International Ultraviolet Explorer and Einstein missions demonstrated for the first time that NASA astronomy science centers could expand the number of users of NASA astronomy data, including researchers new to those wavelength bands.

By 1980, NASA required that observatory-class space astronomy missions set aside a portion of their observing time for guest investigators during the operations phase of the mission. Further, all investigators were formally obliged to provide documentation to accompany the data deposited in the NSSDC. The documentation would allow archival researchers to use the data without the intervention of the PIs.

Although this requirement has always been in place, it has not been consistently enforced until now. For example, in 1983, NASA launched the Infrared Astronomy Satellite (IRAS), which mapped the entire sky in several infrared bands. No guest investigations were included in the mission operations, and no data were released until about a year after the 10-month mission was completed. The initial data processing was carried out entirely by the PI team. In 1986, NASA established the IPAC on the campus of the California Institute of Technology (Caltech) to make the IRAS database available to the astronomy community, and IPAC continues to maintain the IRAS data and to provide access to additional archives and services.

Standardized Data Formats

During the early 1980s, standardized data formats also contributed to expanding the use of data from space astronomy missions. The advantages of standardized formats became so obvious that in 1982 the International Astronomical Union endorsed the use of the Flexible Imaging Transport System (FITS) by all observatories. (FITS had been developed to handle the interchangeability of images obtained with the telescopes of the National Optical Astronomy Observatories and those of the National Radio Astronomy Observatory.) The NASA-commissioned Astrophysics Data Operations Study of 1986,[4] chaired by Franklin Martin, noted that "the standardization of data formats required for analysis is already well advanced; largely through the efforts of National Science Foundation, the FITS format has become a

[4]F. Martin, 1986, *Astrophysics Data Operations*, Greenbelt, Md.: NASA Goddard Space Flight Center.

world standard for astronomical data." NASA formally endorsed the utilization of FITS and created a FITS standards office at the NSSDC. Nevertheless, space astronomy mission centers continued to develop their own brand of data management and analysis tools outside the FITS environment.

The NASA-commissioned Squibb Report[5] not only endorsed FITS as the standard format but also suggested the establishment of wavelength-based archival centers to be responsible for the archiving and accessibility of NASA data. The first such assignment, in 1990, was HEASARC at GSFC, for NASA's x- and gamma-ray data resources. NASA subsequently assigned responsibility for archiving ultraviolet and optical data from space and from digitized ground-based images to the Multimission Archive at the Space Telescope Science Institute (MAST) in 1997 and for infrared and submillimeter data to IPAC in the mid-1990s. Since those original wavelength designations, the centers have become more general and include other wavelength databases in their archives.

While the data archived for the long term were required to be stored in multimission FITS format, data in standardized format were not always immediately available to users. For example, data from the German Roentgen satellite (ROSAT; launched in 1990) were processed and analyzed in Germany in their own binary format, reprocessed at GSFC, analyzed with multimission HEASARC-generated software in FITS format, and then reanalyzed in accordance with a third set of protocols under the Post-reduction Offline Software (PROS) developed at the Smithsonian Astrophysical Observatory (SAO) in an effort to be compatible with the Image Reduction and Analysis Facility (IRAF) shell utilized at STScI for Hubble data. In fact, it was not until 1995 that STScI modified its tables software package to directly support FITS tables, and IRAF support for directly reading and writing FITS format data (limited to images, not tables) was not provided until 1997. These processing challenges presented obstacles for users and limited the impact of the data.

Guest Observer Data Access and the Internet

The two NASA support centers for U.S. users of ROSAT data (at GSFC and the Smithsonian Astrophysical Observatory) provided NASA with experience in the utilization of guest observer facilities (GOFs) during the transitional period, when the Internet was becoming a prime resource for scientific data transmission and analysis. The original plan for ROSAT was that users would first visit SAO to receive some training and experience in analysis software with the help of resident SAO users, who could leverage their very successful experience with the Einstein Observatory. The users could then obtain ROSAT (and other spacecraft) data remotely from Goddard, which they could then analyze from their home institutions. This was a great leap forward in providing service related to non-U.S. missions to U.S. scientists. In earlier missions such as the European X-ray Observatory Satellite and the Japanese Ginga, U.S. scientists had to arrange extensive visits to the home centers of these missions in order to learn how to utilize their data. Soon after the ROSAT data became available, Goddard also made the data from the Japanese Advanced Satellite for Cosmology and Astrophysics (ASCA) x-ray observatory available in the same FITS format and made them amenable to analysis with the multimission tools that were being developed at the HEASARC for ROSAT. As time went on, more and more users preferred to obtain their data remotely without having to visit, sometimes more than once, the mission-specific host facility for training.

[5]G.F. Squibb and C. Cheung, 1988, "NASA astrophysics data system study," in *Astronomy from Large Databases: Scientific Objectives and Methodological Approaches*, A. Heck and F. Murtagh, eds., European Southern Observatory Proceedings No. 28, pp. 489-496.

EXPANDING THE ROLES AND FUNCTIONS OF SCIENCE CENTERS

Proposal Support

The science centers all ultimately assumed the management and support of guest observer proposals to NASA and requests for time on their observatories. The idea of centers actually helping users write their proposals evolved gradually. For instance, the user guides for instruments onboard the Einstein Observatory helped proposers understand the capability of the instruments—that is, what could be observed—and was a first step in proposal support services offered by science centers. By 1990 virtually all centers and GOFs provided realistic simulation software for their observers. At that time, STScI also started selecting the proposals, a function that NASA Headquarters had always managed itself. Space astronomy mission centers had always been responsible for the technical evaluation of proposals and their implementation once selected, but NASA Headquarters had always managed the actual proposal collection, the establishment of peer evaluation panels, and final decisions, including funding level. STScI was able to provide all of those functions under general guidelines from NASA Headquarters, and NASA Headquarters asked STScI to handle proposal selection for HST observations, for HST archival data analysis, and for data analysis in MAST. As a result of STScI's success, virtually all mission-specific proposal reviews are now conducted by the mission science centers.

Education and Public Outreach

Finally, a function common to all centers is a program of education and public outreach (EPO). NASA mandated an EPO program for the HST and included this activity within the STScI. Part of this EPO program was the dissemination of data and research results beyond the research community to students and interested members of the public (see Chapter 5). The STScI approach to EPO allowed for the integration of research results, supported researchers who could discuss the results in various forums, and enabled EPO specialists to work together to greatly raise the visibility of research results and bring the wonder and excitement of astronomic exploration into the homes of all Americans. Since that mandate, NASA has made EPO an essential feature of all NASA science missions, and by extension an essential feature of the astronomy science center.

Finding: The NASA astronomy science centers have transformed the conduct of astronomical research worldwide by allowing remote access to and utilization of NASA astronomy data by researchers, students, and the interested public. In so doing, the centers have been essential to the realization of the scientific potential of NASA astronomy missions.

Finding: The Space Telescope Science Institute provided the community with new standards for user support in proposals and data analysis, established a new paradigm for communicating to the public the discoveries of the NASA astronomy program, and set the first example of a program in science education that was an integral part of science center operations.

2

Functions of Current Science Centers

The current NASA astronomy science centers provide a wide variety of services and functions, which are detailed below and in Appendix A. Overall, these functions center on the dual goals of (1) achieving optimal quality and broad dissemination of data at a reasonable cost through an effective interface between scientists, engineers, and data managers and (2) promoting public awareness of the specific mission. The centers can enable the achievement of these goals by serving specific functions.

SUPPORT OF FLIGHT OPERATIONS

A NASA astronomy science center serves as the link between a spacecraft and scientists on the ground. The spacecraft can be operated either by the NASA astronomy science center itself or by another entity such as a NASA field center. The NASA astronomy science center, in coordination with a distinct operations center if there is one, integrates the tasks supporting the functionality of the satellite, for example, maneuvers of the satellite in space and operation of the instruments on board, with the observations specified by the astronomer to obtain the needed scientific result. The tasks include planning and optimizing the observing schedules; transmitting the commands to the spacecraft instruments; maintaining the correct pointing of the satellite; guiding on the target; ensuring the successful transmission of data from the instruments to the ground and ultimately to the scientist; and managing target-of-opportunity programs that attempt to observe unforeseen but important transient astronomical events such as supernovae.

INSTRUMENT SUPPORT AND CALIBRATION

One essential function of a NASA astronomy science center is ensuring the optimum scientific performance and utilization of all instruments onboard a spacecraft and the transmission of the current state of the instrument performance to the observer. The instrument support includes (1) documenting the instrument's performance; (2) providing support for users to plan their observations; and (3) providing information on the calibration of each instrument to ensure that it is functioning properly and that the data are trustworthy. For imaging devices, this calibration provides information on both angular resolution and the noise levels and sensitivity of the detectors that make up the device. For spectrographs, the wavelength accuracy and sensitivity at different wavelengths must be calibrated to enable comparison with previous space and ground observations. Besides the initial calibrations from the ground and space, calibration must continue throughout the mission lifetime to follow any degradation of the instrument.

The instrument support tasks are often conducted by teams of engineers and scientists. The engineers on the team provide in-depth knowledge of the instrument's technical capabilities and devise and implement solutions to technical problems that arise. The scientists on the team reflect the viewpoint of the user community and ensure that solutions to problems will suit the users' needs. The committee heard repeatedly in discussions with the center staff that close interaction between scientists and engineers, such as in supporting instruments and calibration, is essential to success in the development and operation of the center.

Finding: Space astronomy missions are most effective when there is close interaction between scientists and engineers in the development and operation of the hardware and software to support the missions. This is especially critical for off-site principal investigator teams. NASA astronomy science centers can facilitate scientist-engineer interactions.

DATA ANALYSIS (LEVEL 1 PROCESSING)

For data to be useful to the community, a science center must be able to deliver useful data—that is, data that are partially processed—promptly (usually within 24 hours) to the scientist. Experts at the center must design and operate a software pipeline that starts with the raw data coming from the instrument on the satellite, corrects for the satellite movements and instrument calibrations, and produces data files, as images or tables, that the scientist can use to quickly evaluate the quality of the observation. These quick-look products can be used to detect any problems with the observation, such as instrument failure or abnormal background levels, that would require a reobservation of the target. In addition, these files are often the first step of the detailed analysis by the scientist. It is important for this data analysis functionality to be in place by the time the first information arrives from a space astronomy mission.

ARCHIVING AND DISTRIBUTION TO THE COMMUNITY

The NASA astronomy science center is responsible for creating the final calibrated dataset and sending it to an archive, as detailed in the specific NASA requirements for the mission. Generally, this archive must be durable, support diverse users, and allow international access. The archive adopts community-recognized and NASA-approved standards for data and services, as outlined for each mission; maintains metrics on data used and users; provides high-quality, reliable data in a timely fashion; and maintains storage devices, software, access modes, and distribution media that can evolve with the advance of technology. It supports mechanisms such as user advisory groups to receive community input and guidance and provides user services for the expert and novice. The archive typically preserves Level 0 (raw measurements), Level 1 (calibrated science data), Level 2 (data with coordinates, other information), and Level 3 (products). The final products typically include object catalogs, spectra, and images. The major archive centers currently exist at the Space Telescope Science Institute (STScI) (Multimission Archive at the Space Telescope Science Institute (MAST), for ultraviolet and optical data); at Goddard (High Energy Astrophysics Science Archive Research Center, HEASARC, for x-ray data); and at the Infrared Processing and Analysis Center (IPAC) (Infrared Science Archive, IRSA, for infrared data).

SOFTWARE DEVELOPMENT AND DOCUMENTATION FOR SCIENCE ANALYSIS

Most users rely on the science center to provide the basic software programs that enable detailed analysis of their observations and those in the archive. This software development effort incorporates the expertise of the instrument developers and produces a software package that is easy to learn and that can be run on a variety of computer systems by a diverse group of users. The center provides documentation complete with worked, relevant examples of each use, taking the user from the data provided by the satellite or archive to the finished product. The software and documentation are updated as the system changes.

Often these software packages perform similar functions. However, because the packages are developed by different groups for different missions, they can at times include widely divergent processes for performing similar actions. In these situations, users must spend considerable time and effort on retraining themselves. In testimony to the committee, users stressed the desirability of common software packages.

Finding: The most efficient way of minimizing the effort and time spent by scientists to learn new programs is using common software across missions.

HELP DESK AND OTHER USER SUPPORT

Centers provide help desks to provide prompt replies to e-mail queries and, possibly, telephone support, generally during business hours on weekdays. They generally provide other online help such as tutorials and frequently asked questions so that information is available 24 hours a day, 7 days a week, especially when the help desk is closed. Researchers can also obtain user support from each other by accessing wikis[1] and online discussion groups. However, for complex questions or problems dealing with software, reduction, proposal input, and observation and scheduling that are not solved elsewhere, the help desk provides the best and most up-to-date expertise. In most cases, this support eliminates the need for a user to travel to the center and enables reduction of data at the user's institution. All NASA astronomy science centers currently maintain help desks, but the committee heard from users that the response time depends on the size of the center and the number of people at the help desk. The days leading up to a proposal deadline appear to be especially stressful for users and center staff alike.

Finding: Adequate help desk staffing and online support are critical functions of centers, especially for small centers that do not have much other user support.

USER WORKSHOPS AND SYMPOSIA

Each new mission creates software for accessing and working with the resultant data. User workshops allow new users to learn the software system and the peculiarities of a data reduction package before working on their own at their own institutions. These workshops also provide a forum for scientists to share their experience with the software, to provide advice to the software developers, and, for those with complicated problems, to have their questions addressed in detail. Scientific symposia bring together researchers using the data, researchers thinking of applying for mission time, and the scientists at the center. These gatherings promote healthy exchanges of ideas, bring out problems and needs of the community, and identify directions for future missions. Often, they produce publications that are

[1]A wiki is software that allows users to edit or change Web-based content and the organization of that content.

available to the entire community. Only the major centers generally have the resources and manpower to sponsor workshops and symposia.

PROPOSAL SUBMISSION AND REVIEW

All science centers provide processes for proposal input and review. To be effective, each system must contain efficient documentation on the satellite, the instrumentation, and the submission process. However, the complexity of the proposal process varies substantially from mission to mission. While past missions used the simplest formats of text and e-mail entry, most current missions now rely on form pages and uploads of PDF or postscript files. For the first-time proposer to a mission, the simplest system is often Web-based software with electronic uploads of proposal text: It works on different computer platforms, requires minimal expertise, and allows electronic submission. The most efficient use of scientists' time is a proposal process that takes place in two phases: Phase I involves, largely, a scientific review. It is followed by a technical Phase II, which allows inputting all the details of approved observations but is required only for successful proposers. Problems can arise when software must be downloaded from a center, because many proposers do not have access to software support at their institutions if the programs do not interface easily with existing computers or security systems. Problems typically arise when the proposal software package is large, complex to use, and requires all information to be provided in only one proposal input phase. In these cases, researchers often spend months preparing a working version of the software and learning the idiosyncrasies of the satellite observations. These demands on researcher time are considerable, especially in light of proposal oversubscription rates of 5- to 10-fold on some space astronomy missions and the low rates of success for proposers. In addition, most space astronomy missions use different proposal processes, compounding the time that must be spent on any individual proposal. Examples of these different processes are the Remote Proposal System (RPS) created by HEASARC (and modified for individual missions), the Astronomer's Proposal Tool (APT) system of STScI, and the Spitzer Planning Observation Tool (SPOT) system for Spitzer (see Box 2.1). Of these examples, RPS is the most straightforward for Phase I input; APT is used for both Phase I and Phase II, with Phase II requiring increasingly complex input; and SPOT is the most complex and time-consuming because it requires a full set of information for Phase I.

Finding: A proposal entry that requires minimal technical details for the initial science proposal selection makes the fewest demands on users.

The review process generally consists of several panels of experts who read and evaluate the proposals, then come to the center for face-to-face meetings to discuss and rank them. The center identifies and recruits the reviewers, coordinates the meeting, and provides expertise on any technical questions raised during the review. Since some of the best science involves multiwavelength observations crossing several missions, the efficiency of both writing and evaluating proposals is increased if proposal deadlines, formats, and reviews are coordinated. Many missions now set aside some portion of their observing time for proposals requiring coordination with other space- or ground-based facilities.

GRANT ADMINISTRATION

Typically, all researchers whose proposals are successful in the review process receive some funding for their research. The model that associates research funding with the allocation of observing time ensures the scientific return on a mission. Today, the science centers are responsible for reviewing and

BOX 2.1 Software for Online Proposal Submission and Review

Remote Proposal System (RPS) is a Web-based multimission tool used by scientists to submit proposals for NASA missions. After information is entered, RPS generates a hard copy and the scientist verifies that the proposal information is complete prior to submission. Further information can be found at http://heasarc.gsfc.nasa.gov/rps.

The Astronomer's Proposal Tool (APT) system consists of software that is downloaded (different versions of the software exist for different types of computers) to provide tools for filling out proposal forms and calculating the orbits needed for Hubble Space Telescope data. A relatively simple version is used to input the Phase I initial science proposal, and an in-depth version is used to provide more details for Phase II of an accepted proposal. Further information can be found at http://www.stsci.edu/hst/proposing/apt.

The Spitzer Planning and Observation Tool (SPOT) is a complex, multiplatform software tool to plan and submit an observing proposal to the Spitzer Science Center. It also involves downloading software specific to a computer platform and includes online help. Further information can be found at http://ssc.spitzer.caltech.edu/documents/spot.

allocating the funds for each project, supervising the allocation of funds to coinvestigators, and dealing with the interim and final reports that are a requirement of the grant award. This administrative effort ensures the optimum and proper use of available funding.

SCIENTIFIC RESEARCH

The success of a mission is judged by the scientific output of its community of users as well as of the center itself. Because experience has shown that working research scientists are essential to the successful operation of astronomical observatories, each science center employs Ph.D. scientists who conduct individual research and also do some of the major work of the center. These scientists must have opportunities to conduct their own research, yet they remain primarily facilitators for the research of the outside community.

Scientific research by employees of the center is an integral part of testing software and analysis tools, documenting and fixing problems, and ensuring that the mission is advertised and accessible to the entire community. Center scientists need to have current research expertise to be able to anticipate the needs of users and to provide advice. At the same time, a center must give its researchers opportunities to do their science in order to attract and retain the talent it needs. The opportunities for scientific research depend on the size of the center. The large centers—e.g., STScI, the Chandra X-ray Center, and the Spitzer Science Center—generally provide the most research time for staff. They also have highly successful fellowship programs (see Table A.1) that draw the best postdoctoral young scientists to conduct research associated with the mission either at the center or at a university. These fellows usually gather at the center each year to exchange results and ideas. Besides producing scientific results, the fellowship programs impart vital mission expertise to the outside community because the fellows can transfer their acquired knowledge of working with mission data to their colleagues. Because small missions such as the X-ray Multimirror Mission–Newton (XMM–Newton) and the Far Ultraviolet Spectroscopic

Explorer offer insufficient support for fellows (Table A.1) and center staff have less of their own time for research, a minimal amount of research time must be guaranteed to ensure the mission expertise. Each mission center operates most effectively when it ensures a balance between mission support and individual research opportunities for the staff based on the size of the operation and the size of the user community.

ADVOCACY AND STRATEGIC PLANNING

As the largest astronomy science centers evolve to support their user communities, they naturally become focal points, allowing astronomers to develop strategies for the immediate and long-term future of the areas of astronomy they serve. When a center convenes an annual time allocation committee for reviewing proposals, it will already have a strategy for allocating observatory time and center resources to optimize the overall scientific return. Moreover, the centers host forums in which users and center scientists plan the evolution of the observatory and the center and discuss the scientific opportunities at possible future observatories and their design parameters. Naturally these discussions, and the documents resulting from them, become inputs to strategic decisions in the community and NASA regarding the future of the field.

EDUCATION AND PUBLIC OUTREACH

Due to the wide public appeal of astronomy and the need to improve science education, NASA requires that all science centers support some program of education and public outreach (EPO). These include Web sites (some for the public at large and some for teachers), press releases, teacher training workshops, and EPO grants. The Web sites provide not only images and graphics specific to a mission but also show interplay between scientists and the public through programs such as Ask an Astrophysicist at HEASARC. The level of support for EPO varies with the size of the center (see Appendix A), with large centers having some staff dedicated to EPO and small centers (XMM–Newton, Rossi X-ray Timing Explorer) often sharing resources and staff with their host institutions or umbrella archive centers. Chapter 5 provides a more extensive discussion of education and public outreach activities at the science centers.

3

Models for NASA Astronomy Science Centers

There is a virtual continuum of models for NASA astronomy science centers, and NASA has tried several. The models can generally be characterized as "mission" centers, "science" centers, and "archival" centers, although the boundaries are not sharp. What is certainly true, however, is that centers are usually born with responsibilities for specific space-based astronomy missions.

This chapter discusses five models for science centers—traditional mission centers, Explorer-class mission centers, guest observer facilities, archival centers, and flagship mission centers—and the services they provide. Factors affecting the size and scale of the centers, as well as breakpoints in the level of service, are also discussed.

FIVE MODELS AND THE SERVICES THEY OFFER

Traditional Mission Centers

Traditional space-based astronomy mission centers are dedicated to a single mission. The simplest are exemplified by the centers for small principal investigator (PI)-class missions prior to about 1980. Such PI mission center functions included little more than PI activities that supported mission operations and data analysis, without any significant guest observer or archival research program. Although a NASA mission that does not provide some guest observer utilization is essentially a relic, there are still a few missions, such as the Wilkinson Microwave Anisotropy Probe, for which it makes no sense to have a guest observer program during the mission's operational phases.

The next step up in complexity for a mission center is for an Explorer-class mission with a guest investigator base that is likely to be limited to discipline experts. Recent examples include the Far Ultraviolet Spectroscopic Explorer (FUSE), which is still operating, and the Extreme Ultraviolet Explorer (EUVE), which completed its operations in 2001. In both cases, the PI group can be contracted by a NASA center to operate the spacecraft; the PI group plans and carries out both the science and mission operations with minimal NASA oversight. NASA usually requires a formal guest investigator program and insists that the data be archivable in usable form, but the support for both these activities, FUSE and EUVE, is relatively small. Swift is a current real-time mission that conforms to this general model. Swift science and mission operations are handled by the PI at the Goddard Space Flight Center, with substantial efforts in both mission and science operations contracted to coinvestigators at Pennsylvania State University. The Swift data are promptly available via the High Energy Astrophysics Science Archive Research Center (HEASARC), within seconds for the gamma-ray burst detections, and are quickly accessible and archivable for longer-term analyses.

Explorer-Class Mission Centers

Somewhat more complicated in their mission operations are those Explorer-class space astronomy missions that are expected to have significant guest investigator involvement. Operated out of the Goddard Space Flight Center (GSFC), the Rossi X-ray Timing Explorer (RXTE) mission is an all-guest-investigator mission, without guaranteed observatory time for the scientific staff but with some guaranteed research time that a staff member can use to propose for observatory time. The RXTE science operations center is responsible for the detailed scientific planning of the mission operations, the coordination of the colocated contractor flight operations team, and postacquisition data processing. RXTE staff provide preproposal simulation software and proposal support, as well as data analysis software, to its guest investigator community.

The RXTE center also reviews proposals for guest investigations on behalf of NASA Headquarters. While NASA Headquarters has responsibility for approving the grants and contracts that are associated with guest investigations, the review of proposals (i.e., evaluating proposals for technical merit, convening teams of proposal reviewers from the scientific community for evaluating scientific merit, and making recommendations for proposal acceptance) has now been tasked to mission centers in the overall statement of work.

RXTE, much like other Explorer-class missions, is required to have an EPO plan and has a small budget and fractional staff time devoted to it.

Guest Observer Facilities

A variation on the small mission center described above is a guest observer facility (GOF). GOFs do not have mission operations responsibilities and provide only support to guest observers. A good example is the XMM–Newton GOF at the GSFC, which provides functions specifically associated with NASA support to U.S. guest observers since XMM–Newton is a mission of the European Space Agency, whose science and mission operations are conducted in Europe. Virtually all center-provided functions are now accessed remotely, so that the NASA-specific functions are related to value-added support for proposal preparation and data analysis for U.S. guest observers. GOF provides a user guide for XMM–Newton data analysis, manages the budget proposal process for U.S. guest observers, and provides preproposal support as well as a help desk, although the GOF budget limits the extent of the support that can be provided. But, since the scientists associated with the GOF and the HEASARC are XMM–Newton users, the help-desk support is expert and the standard HEASARC analysis tools[1] for XMM–Newton data are well supported and effectively utilized by the U.S. guest observer community for XMM–Newton. Similar to the XMM–Newton/HEASARC relationship, the Infrared Processing and Analysis Center (IPAC) supports U.S. users of the European Space Agency's Infrared Space Observatory.

[1]HEASARC analysis tools for XMM–Newton data include PIMMS, FTOOL, BROWSE, and XANADU.

Archival Centers

At the mid-range of complexity are archival centers, which provide an umbrella structure for continuing archival and support services after space-based astronomy missions reach the end of their operational lifetimes. The Multimission Archive at the Space Telescope Science Institute (MAST) is located at a mission-oriented center and therefore differs somewhat from HEASARC and IPAC. HEASARC, for example, provides access to ROSAT data and provides user support tools for retrieving and analyzing the data. Archival centers also provide archival services for operational missions such as Swift at HEASARC and the Wide Field Infrared Explorer at IPAC, which is the umbrella for the Spitzer Science Center (SSC) and the Michelson Science Center (MSC).

A practical advantage of associating archival functions with a science center is that the arrangement provides continuing support for at least a skeleton staff of expert users independent of mission requirements. HEASARC is a good example of how the same personnel, data management tools, and basic data analysis software have been used with multiple space-based astronomy mission GOFs operated in the HEASARC environment. The multiplexing of data users and scientific software developers is a win-win-win situation for the stability of center staff, for the efficient utilization of NASA resources, and for the benefit of the user community.

Much like other science centers, the archival centers provide EPO services, help-desk access, and other science support services to the community in addition to the EPO activities of the individual missions associated with the archive center.

Flagship Science Centers

At the high end of complexity for NASA astronomy science centers are those associated with flagship missions like the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope. These centers perform the same basic support functions for guest investigators as do the centers for Explorer missions, including help-desk services, proposal software and proposal preparation support, data archiving, and analysis software, but the scale of each support function is generally much larger. NASA clearly expects that the flagship centers will take extensive responsibility for NASA EPO activities (and will therefore have specialized staff). For example, the flagship centers provide extensive printed and multimedia products for schools and museums, press releases and information for the media, Web-based materials for Internet users, and formal educational products for K-14 curricula. In addition, the flagship centers have generally been given significant responsibilities in all three of the center functionalities just noted: mission operations, science support, and archiving.

There are, however, restrictions on the breadth of activities that NASA will allow the flagship centers to pursue. For example, the charter of STScI specifically precludes it from taking a leadership role in the engineering aspects of new instrument development.

FACTORS AFFECTING SERVICE AND SIZE OF CENTERS

The committee looked across the different kinds of astronomy science centers (in particular at the GOFs and flagship centers) in terms of their budgets, size and role of their staff, centralized or decentralized architectures, and governance structures and oversight, considering the disadvantages and advantages of the various models and approaches. These factors are compared in Appendix A and Table A.1 and are discussed below.

Budgets

It was apparent to the committee that differences between the cost of similar services at various centers could be attributed to specific contractual arrangements with NASA. (An investigation of such contractual details is beyond the scope of this study.) It was also apparent that science centers affiliated with nongovernmental entities and under contract to NASA benefit from a degree of resource stability, at least for the duration of the contract period. Their independence from the government also allows them to advocate for the science community and for their center and to seek sources of funding other than NASA.

Size, Role, and Status of Staff

Some centers have mission operations responsibilities, which automatically affects the size of their staff. All science centers, however, provide a high level of science support to the user community and employ research scientists who are themselves users of the mission data to facilitate the use of data from their particular mission.

The degree to which centers use scientists and the amount of time those scientists have available for independent research distinguishes one model from another. For Explorer-class missions, staff scientists may devote more than a decade of their careers to the mission. Even so, an Explorer mission may not support all of their time, even during its active phase, and not even a fraction of their time for the rest of their career. For longer-lasting centers, however, it is assumed that a center will not be able to attract excellent staff unless it provides guaranteed research support for virtually an entire career, and this assumption changes the scale of science support substantially.[2] It can even be argued that the presence of excellent scientists who are free from support activities and free to pursue their own research serves to attract excellent support scientists. The presence of these scientists, provided through a visiting scientist program, elevates the intellectual atmosphere in which the support scientists perform their functions for the community.

The number of EPO staff also has an impact on the services a center is able to offer. The flagship mission centers have over 20 times as many staff for EPO as Explorer-class or GOF centers (see Appendix A), with NASA having intentionally requested and funded large EPO efforts at the flagship centers. Centers with larger EPO staff can offer a wider range of services and educational tools than the smaller centers. However, individual PI or Explorer-class missions leverage EPO products from their umbrella institutions, such as HEASARC, and are able to reach larger audiences and provide more EPO services than they would on their own.

Centralized Versus Distributed Architectures

Flagship centers such as STScI and the Chandra X-ray Center (CXC) conduct both mission operations and science operations at a central location; other centers follow a distributed approach. The SSC, for instance, handles science operations (e.g., scheduling of observatory sequences), and the Jet Propulsion Laboratory (JPL) and Lockheed Martin Astronautics manage spacecraft engineering operations. Explorer-class missions such as RXTE locate the science operations center and the guest observer facility in a building next to the mission operations center. Explorers such as Swift also use a distributed approach, with a university managing instrument operations, a NASA center operating the satellite, and the NASA archival center, HEASARC, providing archival services.

[2]This research time does not include guaranteed observation time, which is allocated through the peer review process.

Several center staff members reported on the need for strong linkages among operations engineers, instrument teams, software developers, and support scientists. Locating mission operations and science support activities nearby may strengthen those linkages.

Governing Institution and Governance

Science centers take a range of approaches to governance. Exercising a high level of independence, the STScI is governed by a separate association that holds the contract for the STScI, has responsibility for hiring the director and deputy director, and oversees the work of the STScI. SSC and MSC are governed by JPL program management; directorships of the centers are held by academics in the California Institute of Technology (Caltech) Division of Physics, Mathematics, and Astronomy. Caltech manages JPL, so all Caltech policies apply to SSC and MSC. The CXC is operated by the Smithsonian Astrophysical Observatory as part of the Harvard-Smithsonian Center for Astrophysics. The NASA GOFs and HEASARC are government entities under the direction of NASA's GSFC. Figure 3.1 depicts the science centers examined for this study, their host institutions, and the key archives held.

Oversight of Centers

Science centers undergo several types of formal reviews. NASA provides formal management targets that the science centers are obliged to meet and also convenes senior reviews,[3] a means by which the community can help set priorities for the guest observer support associated with each mission. Centers under contract to NASA comply with formal processes such as quarterly reviews and Independent Implementation Reviews. In addition to the NASA reviews, the centers have devised their own performance measures, which often include tracking the number of proposals submitted and accepted for observations on the telescope or observatory, the data ingested and data accessed from the archive, the number of refereed papers published using data from the archive, and observing efficiency.

All centers reported on the user committees (committees of outside users) that provide feedback and direction to the center on its support services. Staff from the centers that were studied commented on the senior review process, finding it to be a form of performance review that ranks the center's scientific contribution relative to that of other centers. Some centers also bring in outside experts to review their EPO activities; others cover EPO performance in the senior review.

SUMMARY

It was clear to the committee that all of the center models could provide valuable services to the community but that the smaller GOF and Explorer-science centers lack the resources and staff to offer a full range of science center services (see Chapter 2). Associating GOFs or Explorer centers with the larger archival centers or flagship mission centers, which have staff and infrastructure in place, enables the smaller centers to leverage skills and services and better serve their scientific constituents.

One benefit of the archival centers is their ability to accommodate mission centers at varying stages of operation and to move science staff among projects as missions start up or wind down, providing stability and flexibility. These archival centers also provide proposal and analysis software, search tools,

[3] NASA's senior review process considers whether to provide funding to extend mission operations and data analysis for any of the operating space science missions beyond their planned mission lifetimes. The senior review process prioritizes those missions that should be extended, based on their scientific value and return, within NASA's available funds. This same senior review process is used for the NASA data centers and archives.

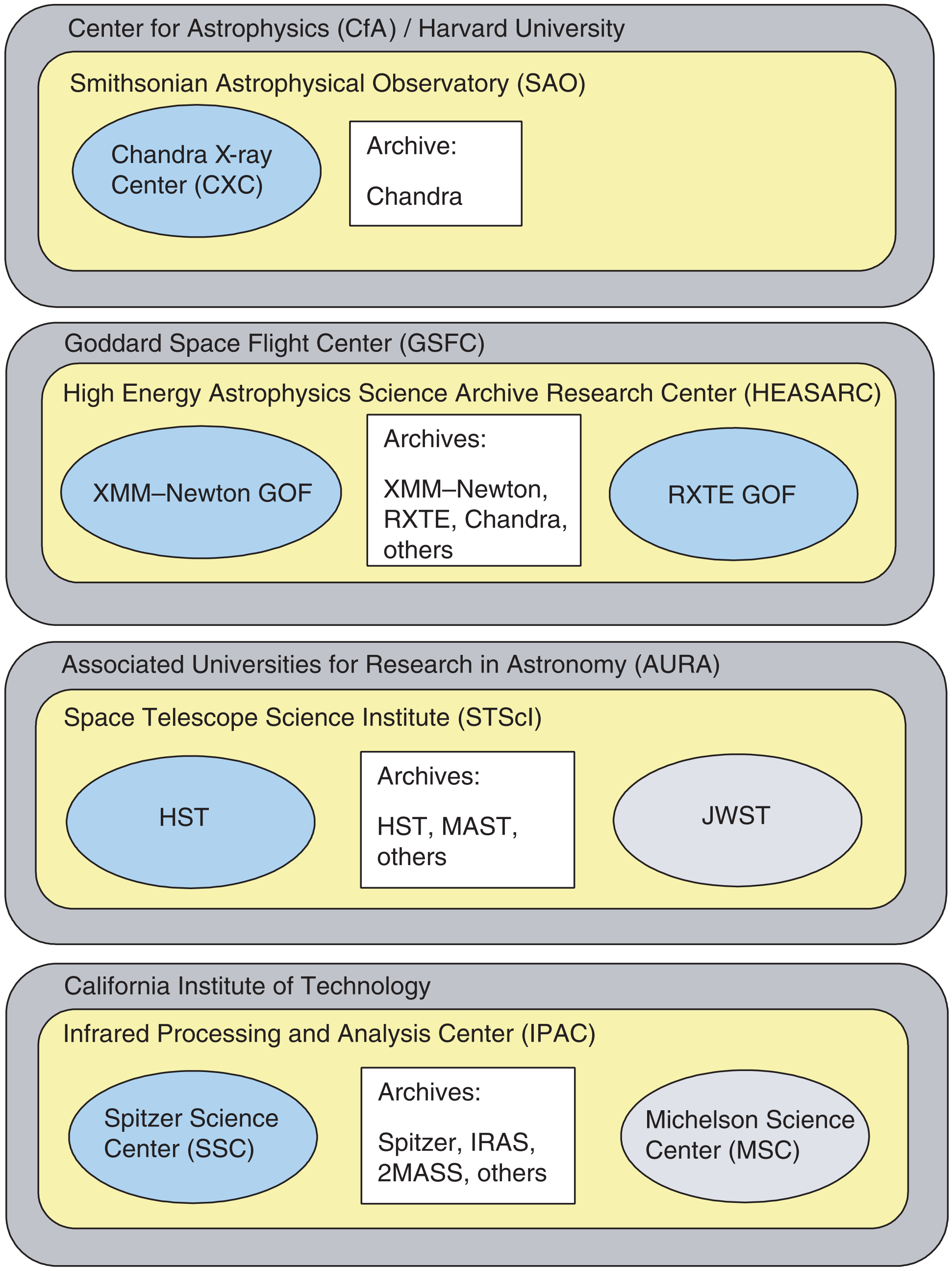

FIGURE 3.1 A guide to the institutional arrangements for the NASA astronomy science centers considered in this study (STScI, SSC, CXC, XMM–Newton guest observer facility, RXTE guest observer facility, and MSC). The largest boxes show the host institutions for the centers, the next-largest boxes (yellow) show the umbrella organizations, and the ovals show the NASA astronomy science centers. The blue ovals are operational centers and the screened ovals indicate missions/centers under development. The white squares show the missions whose data are archived at the umbrella organization. Only the NASA astronomy science centers and their archives considered for this study are included. Umbrella organizations such as HEASARC and IPAC encompass other NASA centers for both mission operations and archives, as described in the text. For definitions for acronyms, see Appendix D.

and other resources that users can apply to multiple databases held by the archive. Further benefits accrue in the knowledge base that staff acquire from one mission to the next, which allows for transferring best practices and lessons learned among missions.

The committee viewed the presence of research scientists and visiting scientists as a positive enhancement of a science center's role and its ability to provide an exciting and intellectually rich environment. It was recognized that staff scientists can best serve the community if they are themselves involved in active research, so that some fraction of their salaried time should be allocated for their own research. The committee believes, however, that it is not necessary to have full-time researchers for a science center to serve the community effectively and that all the scientists at a center should be involved, at some level, in facilitating the mission.

The committee saw no evidence that the centers as a whole prefer one approach or the other—centralized or distributed. Several center staff members emphasized the need for strong linkages among operations engineers, instrument teams, software developers, and support scientists.

The committee does not view the differences in governance at the centers as having any effect on the services provided or on the ability of users to influence a center's functions. The committee believes that oversight of the centers is sufficient. A center's independence from NASA and an intermediate degree of governance structure, however, did appear to have advantages for the long-term security of a center. For example, STScI and CXC are under contract to NASA and are not dependent on annual appropriations in the NASA budget cycle, as are the GOFs and HEASARC. Centers that are not governmental can advocate for themselves and seek sources of funding other than NASA to support their activities. At the same time, the centers that have intermediate governance structures may take longer to respond to community input as a result of the additional layer of management in their systems.

FINDINGS

After visiting the centers and analyzing their activities—mission responsibilities, operations, personnel levels, help desk, archiving, and EPO activities—the committee discerned break points in service that, not surprisingly, correlate with levels of funding. These are readily deduced from an analysis of Tables A.1 and A.2 in Appendix A.

Seen from a broad perspective, Explorer-class missions and GOFs funded at less than $10 million per year struggle to supply basic services to the community. On the positive side, because these centers are embedded within larger NASA field centers, their staff can call on the time and expertise of a wide variety of people, an efficient way to accomplish an array of tasks. This access and the often-heroic efforts of very dedicated and highly motivated staff make these centers somewhat effective in serving the research community, but only minimally so, as the committee heard in testimony and learned from site visits. These centers simply do not have the funding to support a wide enough range of activities to move the scientific research crisply ahead and derive the full benefits of the observing facilities. Funding at $10 million or below does not allow for much, if any, instrument support and calibration, data analysis and Level 1 processing, software development, help-desk activities, user workshops, or symposia. EPO at these centers struggles to find a voice. Perhaps most important, research by center personnel, postdoctoral fellows, and visiting scientists, essential for deriving the maximum benefit from a facility because of its catalytic effect on flight operations, software development, help desk, and other services, cannot be funded. Despite the remarkable, even heroic, efforts of the staff at these facilities, the committee feels that the funding is insufficient to support the community as astronomy moves toward more and more multiwavelength research.

STScI, Chandra, and SSC/IPAC on the other hand, funded at several tens of millions of dollars per year, set the standards for the provision of services to the community.[4] Clearly the research community has come to rely on the service these facilities provide. Also, as mentioned elsewhere in this report, the full complement of services and the integration of the continuum of expertise from flight operators, engineers, programmers, researchers, EPO specialists, and a variety of support personnel multiply the value of the space observatory and the scientific results that can be achieved beyond what could be achieved with a linear extrapolation of the funding.

Owing to the lack of models of intermediate size ($20 million to $30 million), the committee could not assess the potential efficacy of centers in this case. Where such centers would fall on the curve of funding versus service remains to be explored. However, one can posit that there must be a threshold level of service (and hence funding) below which the synergistic effects of the full complement of talent, activities, and services—and hence the overall value to the science and the nation—drop, most likely, rapidly.

After considering various models for NASA astronomy science centers and the factors affecting their size and utility to the community, the committee finds that CXC, STScI, and the science center complexes in Pasadena, California (JPL-Caltech) and Greenbelt, Maryland (GSFC) contain a number of activities that could (in principle, and often in practice) grow with respect to both personnel and physical plant resources. These science centers should become the natural hosts for continuing support of ongoing research that utilizes NASA's data resources after individual mission centers have outlived their charters. They make up an effective infrastructure that could serve both existing and planned missions well. The committee recognizes, however, that missions such as the Terrestrial Planet Finder, Laser Interferometer Space Antenna, Space Interferometry Mission, and Constellation-X, if they are developed, might need more capabilities, expertise, and user support services than are provided by these four science center complexes and might even justify additional NASA astronomy science centers in the future.

Finding: Embedding guest observer facilities in existing science centers such as the High Energy Astrophysics Science Archive Research Center provides for efficient user support, especially when the scope of a space mission does not warrant a separate science center.

Finding: The Chandra X-ray Center, the Space Telescope Science Institute, the High Energy Astrophysics Science Archive Research Center, and the Infrared Processing and Analysis Center have sufficient scientific and programmatic expertise to manage NASA's current science center responsibilities after the active phases of space astronomy missions are completed.

Finding: The ability of the Chandra X-ray Center, the Space Telescope Science Institute, the High Energy Astrophysics Science Archive Research Center, and the Infrared Processing and Analysis Center to provide the appropriate level of support to the scientific community depends critically on the extent to which they can attract, retain, and effectively deploy individuals with the mix of research and engineering skills necessary to maintain continuity of service.

[4] The committee did not obtain budget data for archive centers such as HEASARC and IPAC because they were not included in the statement of task for the study. However, the committee considered the archival centers in its deliberations, and the committee chair conducted site visits of HEASARC and IPAC.

4

Data Archiving in the Science Centers

THE IMPORTANCE OF ARCHIVAL ACCESS

Access to archival material is becoming increasingly important for all space science disciplines because data are often analyzed more than once and because scientists combine existing data sets across traditionally separate wavelength boundaries. The science centers have become archival centers, and today these online archives serve as the primary point of access to mission data, both raw and calibrated.

Not only are the archives the keepers of the raw observations, but they also provide direct access to calibrated versions of their data products, with online documentation and searchable databases linked to the literature. This "shrink-wrapped" feature of modern archives makes it easier for astronomers to combine data across various subdisciplines, a task that would have been difficult even a few years ago when all astronomers had their own sets of tools and did most of the data reduction themselves.

Archives are a necessary part of an ongoing mission in that they need to furnish rapid access to science-quality data. They also need to capture the relevant information for future recalibration and any modifications and changes that were made to the data reduction pipelines. This provenance information is mandatory not only for a consistent data set but also for legacy uses of the data.

SUSTAINABLE, LONG-TERM ARCHIVES

Archives play a role in efforts that go beyond the space astronomy mission at hand. In most cases, the data sets produced by NASA's space astronomy missions will be a valuable asset for the community even decades after the mission's completion—for example, the International Ultraviolet Explorer (IUE) and the Infrared Astronomy Satellite (IRAS). The long-term preservation and continued curation of such data sets are extremely important. These responsibilities present particular challenges for the science centers and have become an important part of their long-term mission. A key question is this: Once a space astronomy mission has completed its operational lifetime, should its archive remain at the location that managed the archive during the mission, or should it be migrated to a central facility where economies of scale might provide a cheaper solution to long-term preservation?

The decision on where to keep a long-term archive should consider what makes an archive usable and sustainable for the community, beyond the minimal goals of preserving the bytes. The committee describes a sustainable archive as one that

- Continually facilitates the production of new scientific results;
- Has a strategic goal to enable more and better science;
- Contains high-quality, reliable data;
- Provides simple and useful scientific tools to a broad community;
- Provides user support to the novice as well as to the power user;
- Has many diverse uses (and users);
- Has a core group of users for whom it is an everyday tool;
- Collects metrics that track usage and science output;
- Is properly curated (e.g., errors discovered are documented and fixed);
- Adapts and evolves in response to community input; and
- Has an adequate mix of developers, scientists, and tech support staff.

In spite of the considerable efforts of archive staff to capture as much of the metadata about the particular instruments as possible, the scientists dealing with the quirks of an instrument over the years will always have a much more intimate understanding of the systematic errors in the data products. It is important for the mission to develop good metadata and documentation to ensure the long-term accessibility and usability of its mission data. NASA astronomy science centers can play an important role over the long term in capturing as much of this knowledge as possible during the mission phase, but they should also strive to retain the knowledge as long as necessary, using the above criteria.

ORGANIZATION BY WAVELENGTH

It is clear that there is a natural migration of older data sets into centralized facilities and that not every mission will (or should) retain its own separate archive. Although many archives specialize in broad wavelength ranges,[1] those wavelength distinctions have loosened over time. There are also value-added services such as the Astrophysics Data System (ADS)[2] (http://adswww.harvard.edu/) and the NASA/Infrared Processing and Analysis Center (IPAC) Extragalactic Database (NED)[3] (http://nedwww.ipac.caltech.edu/), which link the data sets to the literature. Today many astronomers are using these services several times a day. These archives are of course the primary guardians of the data sets from their main missions, the Hubble Space Telescope (HST) at the Space Telescope Science Institute (STScI); Compton Gamma Ray Observatory, Uhuru, Advanced Satellite for Cosmology and Astrophysics, the Roentgen satellite (ROSAT), and many others at HEASARC; the Einstein and Chandra (http://cxc.harvard.edu/cda/) for the Chandra X-ray Center (CXC); and IRAS, Two Micron All Sky Survey (2MASS), Spitzer, and many others at IPAC.

[1]The UV-optical data sets are migrating to the Multimission Archive at the Space Telescope Science Institute (MAST) at http://archive.stsci.edu/; the near- and far-infrared archives are at the Infrared Science Archive (IRSA) at http://irsa.ipac.caltech.edu/, at IPAC; and the high-energy data sets are moving to the High Energy Astrophysics Science Archive Research Center (HEASARC) at http://heasarc.gsfc.nasa.gov/ at the Goddard Space Flight Center.

[2]ADS, operated by Harvard and funded by NASA, contains 4.8 million searchable bibliographic records. Full-text scans of many of these records are viewable free via a browse engine.

[3]NED, operated by the Jet Propulsion Laboratory and under contract to NASA, contains 14 million names for over 9 million extragalactic objects and over 3.3 million bibliographic references.

This natural organization by wavelength has been rather efficient, since the data sets can be curated using a shared expertise at the respective science centers. The personnel at the centers have an enormous collective expertise related to these missions. The help desks are maintained by scientists who have had first-hand experience in developing and/or using these missions. The wavelength-specific software tools are also maintained and distributed through these channels.

Finding: Successful research using archival data sets is dependent on the resident expertise and corporate memory that reside at the science centers.

ARCHIVES AS A SYSTEM

Scientists try to stress the capabilities of any instrument they use to make new discoveries. As a result, most discoveries are done at the edges: the most distant quasar, the faintest arc in the image of a distant galaxy, or the weakest spectral line in a noisy spectrum. Each new space astronomy mission provides a new look at the universe, fainter than before or opening a new domain in the electromagnetic spectrum.

The multiwavelength data available in the different mission archives offer a way to create new "edges." By combining data sets from different wavelengths, astronomers have found hundreds of brown dwarfs; discovered the most distant galaxies; discovered that the x-ray background was dominated by active galactic nuclei; and established the connection between gamma-ray sources and radio-bright active galaxies.

The NASA astronomy science centers played a crucial role in changing the scientific paradigm of how space science data are analyzed. Figure 4.1 quantifies archival data collected by HST and shows how retrievals increased following the release of the Hubble Deep Field data. The Hubble and Chandra Deep Fields and some of the selected areas—for example, the Great Observatories Origins Deep Survey (GOODS) at http://www.stsci.edu/science/goods/—are prime examples of collecting data at multiple wavelengths over the same area. Archival grants provided the initial motivation for astrophysicists to start analyzing archival data. Today it seems to be almost natural that many data sets are analyzed by numerous scientists, but 10 years ago this was the exception.

Finding: Continued access to mission data across a broad range of wavelengths is of utmost importance to the whole community.

As the use and reuse of data are crossing wavelength boundaries, it is important to consider what is necessary to support such activities. The most important capability from an astronomer's perspective is that of locating an archive that contains data from a particular region of the sky, in a particular waveband, with a particular instrument. Doing so is possible today, but the procedure is cumbersome.

STANDARDIZATION AND REUSE OF TOOLS

To facilitate comparison, different archives have to be able to provide data in a common format, thereby enabling easy cross-matching of different catalogs and displays of images on the same scale and orientation. Astronomy has a long tradition of common standards, most notably, the Flexible Imaging Transport System (FITS) format. All astronomical software has been able to read FITS images and binary tables for at least two decades. At the same time, it took considerably longer to reach consensus on a common format for spectra. The FITS format was a very important step in allowing the utilization of different data sets for astronomy research.

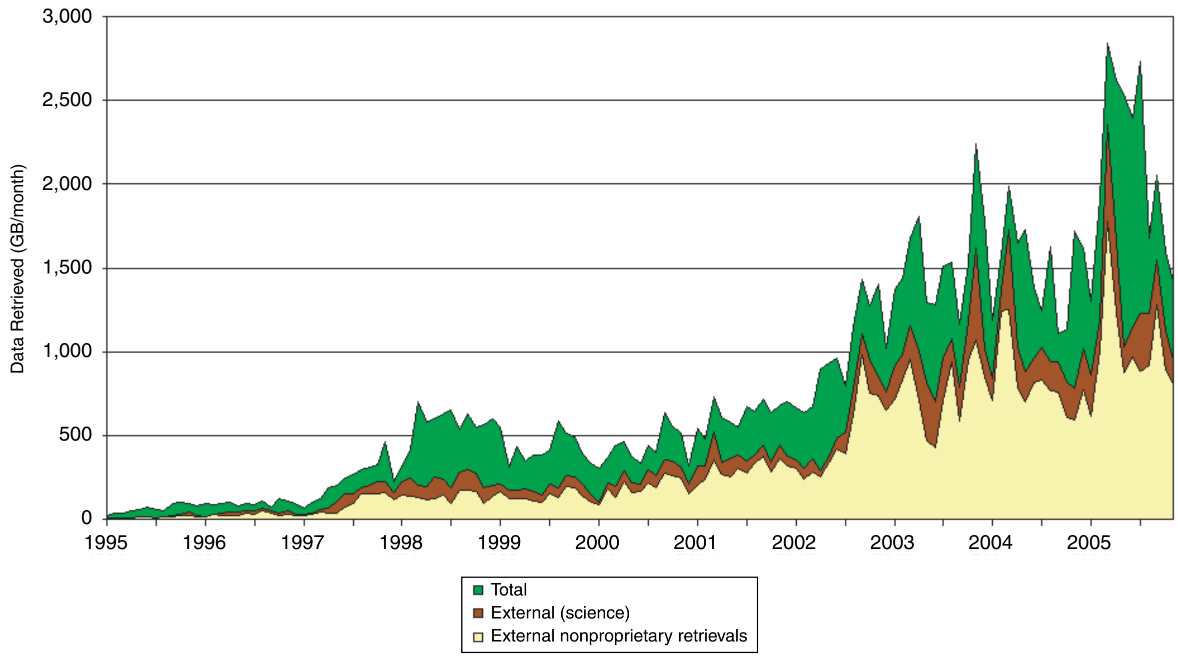

FIGURE 4.1 Usage of archival data from the Hubble archive. The brown area shows PI access, roughly steady in time, while the yellow area is non-PI usage, clearly growing rapidly since 1997, following the release in 1996 of Hubble Deep Field project data. SOURCE: Megan Donahue, Michigan State University, presentation to the committee on November 18, 2005.

Finding: Software tools that use standard data frameworks such as FITS provide the best means to cross-query wavelength-specific data sets.

CURRENT STATUS

The National Virtual Observatory (NVO), at http://www.us-vo.org/, is beginning to coordinate standardization efforts and to provide the first data integration and federation tools and applications. To date, the staff from STScI, HEASARC, and CXC have played significant roles in defining standards within the context of the NVO itself and the NVO as a member of the International Virtual Observatory Alliance. Standards, however, are beneficial only if they are accepted. There are encouraging signs that science centers are implementing the virtual observatory (VO) standards. Indeed, much development work in the centers over the last year has been on increasing compatibility with the VO standards. The HEASARC DataScope,[4] the IRSA Footprint Service,[5] and the STScI Hubble Legacy Archive[6] projects

[4]The HEASARC DataScope is hosted by NASA/HEASARC. It allows for information about a certain point or region of the sky. When a target is entered, it returns relevant information on the target.

[5]The IRSA Footprint Service provides an inventory and data exploration service for navigating the infrared sky. It is operated by the Jet Propulsion Laboratory at the California Institute of Technology and is funded by NASA.

[6]The Hubble Legacy Archive is currently a conceptual idea for adding fast data access to MAST. New features include immediate access to calibrated HST data, improved astrometry, and footprint services that give accurate image boundaries. This archive will be a part of MAST.

are good examples of these efforts. The upper management of the archives at the science centers has embraced this direction, and the archives are currently implementing medium-term measures to achieve VO standards.

NEAR FUTURE

If the current trend to strong collaboration continues, the archives supported by the science centers will form a homogeneous, easy-to-use system that is integrated from a user's perspective. Each wavelength regime, however, will retain its own responsibilities for the long-term curation and preservation of the expertise. Such a system of archives needs to be sustainable. What does this sustainability imply? The committee concludes that archives have to form a system that does the following:

- Provides services that tap resources across the whole community, not just those from one center;
- Facilitates the adaptation of community-wide standards for data and services;
- Provides a mechanism for collaborating on and sharing broadly useful software with other archives and with the astrophysics community;
- Provides data, software, standards, and documentation;
- Offers, on a regular basis, tools to teach users and developers; and
- Supports international access to data and services.

Further discoveries will stem from the analysis of multiwavelength data sets. As access to remote data improves and user-friendly tools to support multiwavelength analysis become available, more astrophysicists are expected to rely on these archival data sets on a daily basis. Such a likely outcome will bring additional challenges and raised expectations. Reliability of the data archives will be crucial because more of the community's research will depend on it. Performance will also be critical when users expect to get their data in seconds rather than hours.

Data curation and provenance are notoriously labor intensive and might present the biggest challenge. As data processing evolves and the archives store derived data sets, possibly from the combination of multiwavelength data (see mention of GOODS above), it will be increasingly important to track the processing trail of the derived products. In a world of more and more data, finding the relevant data sets and assessing their quality and reliability will be also increasingly important, so that the continuous evolution and curation of data—even old mission data—become crucial. Centers could take on more active roles in recent efforts to move data analysis software to the next level, in which a universal (common and distributed) analysis infrastructure supports many instrument-specific applications, some which are developed in the community and some at the center.

As software technology evolves, it is expected that it will be progressively easier to calibrate the data as they are accessed, guaranteeing the most up-to-date version for everyone. Calibrating data as users extract a given data set will require increasingly more computational resources to be co-located with the archives. This will expand the level of services that the archives will be asked to provide.

5

Education and Public Outreach

Astronomy has a special appeal to the public by virtue of the richness of its images, the exotic environments in which it plays out, and the fundamental questions it asks about cosmic origins. No doubt, the generous public support for NASA's astronomy research stems largely from astronomers' success in making the fruits of their research accessible and appealing to many people. Moreover, astronomy attracts many young people into careers in science. Astronomers have a responsibility to continue these efforts and especially to help improve science education in the nation's schools.

Astronomical observations can illustrate universal concepts—such as how scientists interpret inherently uncertain or noisy data or why it is useful to observe a phenomenon at multiple wavelengths—which are fundamental to scientific literacy. Recognizing this value, NASA has mandated that science centers support programs in education and public outreach (EPO), and every NASA astronomy science center has responded to this mandate.

PUBLIC OUTREACH

The most visible products of the EPO efforts at the science centers are their Web sites:

- The High Energy Astrophysics Science Archive Research Center (HEASARC) of NASA Goddard Space Flight Center (GSFC), http://heasarc.gsfc.nasa.gov/docs/outreach.html;
- The Space Telescope Science Institute (STScI), http://www.stsci.edu/outreach/;
- The Chandra X-ray Center (CXC), http://chandra.harvard.edu/pub.html; and
- The Infrared Processing and Analysis Center (IPAC), http://coolcosmos.ipac.caltech.edu/.

Each Web site is rich with press releases, images, and animations illustrating and describing cosmic sources seen in several wavelength bands. These sites also provide educational resources intended for use by teachers and students, and they may even engage and motivate students enough to pursue careers in science.

In addition to the Web sites, these NASA astronomy science centers, especially those for the flagship missions, support other public outreach efforts. They provide information to museums and print and broadcast media and distribute popular materials such as posters, postcards, and stickers that serve an EPO function. STScI, CXC, and IPAC also administer programs that provide supplemental grants to enable scientists using their facilities to develop EPO resources. These grants enable university scientists and NASA astronomy science center staff to coordinate their outreach efforts to students and the public. In fact, the EPO groups at the science centers include active research scientists and routinely consult with other scientists at the centers and with guest investigators to develop press releases and scientific information for the public.

Finding: A close coupling between a science center's research scientists and its EPO effort is a hallmark of a successful science center EPO program.

The Jet Propulsion Laboratory (JPL) has developed an EPO Web site (http://planetquest.jpl.nasa.gov/index.cfm) devoted to the quest for extrasolar planets, by ground-based observatories and by existing and proposed space missions such as Spitzer, Kepler, the Space Interferometry Mission, and the Terrestrial Planet Finder.

Several smaller missions have their own EPO Web sites, such as those for the Wilkinson Microwave Anisotropy Probe (http://map.gsfc.nasa.gov/) and the Galaxy Evolution Explorer (http://www.galex.caltech.edu/index.html). HEASARC has delegated responsibility to Sonoma State University to develop EPO programs for the Swift (http://swift.sonoma.edu/) and Gamma-ray Large Area Space Telescope (http://www-glast.sonoma.edu/) missions.

Images and press releases provided by the science centers appear frequently on the front pages of major national newspapers and magazines and in almost every physical science textbook. The Web sites are among the most frequently visited scientific sites on the Web. For example, the Astronomy Picture of the Day (http://antwrp.gsfc.nasa.gov/apod/astropix.html), supported jointly by NASA GSFC and the National Science Foundation (NSF), is one of the most popular Web sites in all of science, with more than 600,000 page visits per day.

These EPO programs have greatly increased the public's appreciation and understanding of NASA's efforts in space astronomy.

Finding: The public outreach efforts of the astronomy science centers have a major national impact.

During its data gathering, the committee learned that NASA Headquarter's approval process for EPO products is adding time and expense to NASA astronomy science center public outreach efforts. The committee believes that the science centers have sufficient expertise and competence to vet their own education and public outreach products.

K-12 EDUCATION

In its recent report, *Rising Above the Gathering Storm*, the Committee on Prospering in the Global Economy of the 21st Century listed four priority recommendations for ensuring American competitiveness, the first of which was to "increase America's talent pool by vastly improving K-12 science and mathematics education."[1] Specific strategies to achieve this goal included funding summer institutes to

[1]National Research Council, 2007, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.* Washington, D.C.: The National Academies Press, p. 5.

support up to 50,000 teachers each year "to keep current with recent developments in science, mathematics, and technology and allow for the exchange of best teaching practices"[2] and to develop "K-12 curriculum materials modeled on a world-class standard."[3] The science centers can and should make a significant contribution to this strategy.

There is no bright line between public outreach and education. All the public outreach resources provided by the astronomy science centers have educational value. Teachers reported to the committee that they use these resources to augment classroom lessons, and many students explore the Web sites to find materials for essays and term papers and often for the sheer joy of learning. In fact, science center Web sites, perhaps more than science lessons,[4] can motivate students to pursue careers in science.

The astronomy science centers already provide resources specifically intended for K-12 school teachers. For example, they conduct teacher workshops, support programs for teachers and students to visit the centers, and post lesson plans on their Web sites. In some cases, the centers actually provide observing time on spacecraft for teachers and their students; an example is the observing time provided in the science education workshop for teacher leaders jointly sponsored by the National Optical Astronomy Observatories and the Spitzer Science Center (http://www.noao.edu/outreach/tlrbse/).

Despite these efforts, the troves of scientific information provided by the EPO programs of the science centers have not found their way into lesson plans or student activities in most K-12 classrooms. Why is this so? Educators interviewed by the committee suggested that most teachers simply do not have the time to develop lesson plans ab initio. To introduce new material, teachers need lesson plans that

- Are easy to find;
- Have been designed iteratively through field testing and evaluation in actual classrooms;
- Include student-centered hands-on activities;
- Can be completed in a limited time period;
- Work well with standard curricula at appropriate grade levels;
- Have clearly defined learning goals that meet state and national standards; and
- Come packaged with protocols for measuring learning effectiveness.

Most important, these lesson plans must be embedded in an infrastructure that supports teachers, including Web-based teacher guides and workshops for training teachers.

Individual science centers do not have the personnel or resources to carry out ambitious programs in curriculum development. However, they could have a much greater impact on K-12 education. They could, for example, establish strategic collaborations with each other and with other organizations having experience in developing curriculum materials and in-service teacher training.

Teachers will find it much easier to adopt curriculum resources related to NASA astronomy missions if these resources all have the same look and feel. Moreover, some of the most important scientific insights that students can gain come from comparing what we see from space and from the ground. Through such comparisons, students can understand much better the limitations imposed by atmospheric transmission, angular resolution, and signal/noise. They will also see that we can learn much more about the universe by observing its constituents in several wavelength bands rather than just a single band.

Moreover, by partnering with existing organizations having experience in providing professional development for in-service teachers, the science centers can reach far more teachers than they can on

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[2]Ibid, p. 5.
[3]Ibid, p. 6.
[4]Weiss et al., 2003, *Looking Inside the Classroom: A Study of K-12 Mathematics and Science Education in the United States.* Chapel Hill, N.C.: Horizon Research, Inc.

their own. We have already witnessed a successful example of such leverage in the partnership of the Spitzer Science Center with the ongoing Teacher Leaders in Research Based Science Education program. This program, sponsored by the NSF through the National Optical Astronomy Observatories, reaches the formal education community through a national audience of well-trained and -supported middle and high school teachers.

NASA and the NSF have defined their roles such that space-based astronomy research is the province of NASA, while ground-based (primarily optical and radio) astronomy research is the province of NSF. But maintaining this distinction is counterproductive when it comes to K-12 education. In fact, some of the greatest opportunities for the science centers to increase their impact on K-12 education come from partnerships with the NSF. For example, the National Virtual Observatory (NVO), at http://www.virtualobservatory.org/, is a major NSF-supported project to develop a set of online tools to link all the world's astronomy data. The NVO, with several partners, is developing tools and resources for students to explore and analyze astronomical data from many different instruments, at all wavelengths of the electromagnetic spectrum from radio to gamma rays. Likewise, other projects supported by the NSF and other organizations, such as the Hands-on Universe (HOU) project[5] (http://www.handsonuniverse.org/) of the Lawrence Hall of Science, Project CLEA[6] (http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html) at Gettysburg College, and the Digital Universe Atlas at the American Museum of Natural History[7] (http://www.haydenplanetarium.org/hp/vo/du/) provide venues for the science centers to leverage their efforts in K-12 education.

Finding: Astronomy science centers have developed valuable resources for K-12 education, but developing a coherent strategy that can have a greater educational impact remains a major challenge.

[5]HOU allows students to request observations from an automated telescope, download the images from an archive, and analyze the images using provided software. HOU is run by University of California, Berkeley.

[6]Contemporary Laboratory Experiences in Astronomy (CLEA) provides high school and college students the opportunity to practice modern astronomical techniques in the laboratory using dedicated software programs. CLEA is supported by Gettysburg College and the NSF.

[7]The Digital Universe Atlas is run by Hayden Planetarium with significant support from NASA. The Atlas allows for casual browsing and navigation around a highly detailed three-dimensional map of the universe via a free software download.

6

Best Practices and Recommendations

As NASA builds and operates space astronomy observatories in the future, it will need to assign mission responsibilities to existing astronomy science centers or develop new centers. NASA is also responsible for assessing the effectiveness of its current portfolio of science centers.

Through the course of this study, the committee obtained written information and heard presentations from the leaders of the various science centers. The committee also invited experts, from research scientists to high school science teachers, to speak with the committee to explore the full range of center services. The chair of the committee also visited the science centers. Informed by these experiences and the data it gathered for the study, the committee makes three recommendations on existing and potential future astronomy science centers.

Recommendation 1. NASA should establish a large new science center only when the following criteria are met: (1) the existing science centers lack the capacity to support a major new scientific initiative and (2) there is an imminent need to develop an infrastructure to support a broad base of users.

The committee concludes that the four existing major astronomy science centers are sufficient to meet the needs of the astronomical community for the foreseeable future. These four centers—the Chandra X-ray Center (CXC), the High Energy Astrophysics Science Archive Research Center (HEASARC) at Goddard Space Flight Center, the Infrared Processing and Analysis Center (IPAC) at the California Institute of Technology, and the Space Telescope Science Institute (STScI)—have evolved to meet the community needs to support high-energy astrophysics (at HEASARC and CXC); optical, ultraviolet, and near-infrared astronomy (at STScI); and far-infrared astronomy (at IPAC). In addition, a number of smaller missions provide their own user support while they are active and transfer the responsibility for data archiving to the major centers after their active phases.

Should the criteria in Recommendation 1 be met and a decision be taken to create a new center (or centers), the committee has identified a set of best practices that can assist in developing the new center(s) (Box 6.1).

Recommendation 2. NASA should adopt a set of best practices as guiding principles to ensure the effectiveness of existing flagship and archival NASA astronomy science centers and to select the operational functions of any future centers.

Recommendation 3. NASA should ensure that its astronomy science centers cooperate among themselves and with other agencies to develop strategies and plans for

- **Developing common protocols and formats for proposal entry;**
- **Developing a universal infrastructure for data formats and metadata, archiving, and retrieval and analysis tools; and**
- **Providing curriculum materials and professional development programs for K-12 teachers.**

As data on cosmic phenomena become available in many wavelength bands, the process of obtaining, analyzing, and interpreting them is becoming an increasingly important mode of astronomical discovery. Providing tools that are user-friendly, platform-independent, and common to all wavelength bands will enable the community to participate in multiwavelength research. For example, it is inefficient and wasteful not only of programming time but also of a working scientist's time for the centers to require independent protocols and formats for proposal entry.

Likewise, the process of discovery through analysis of multiwavelength data sets becomes much more efficient if the individual scientist can work with data that are stored in universal formats and can be retrieved and analyzed with common software packages. Moreover, these common formats and protocols should be compatible with data from ground-based as well as space-based observatories. These are the goals of the National Virtual Observatory (NVO). NASA should ensure that the science centers cooperate among themselves and with NSF-supported observatories such as Gemini and the National Radio Astronomy Observatory to develop strategies to achieve this vision.

The development of both K-12 classroom resources and infrastructure for the continued education of teachers is critical for ensuring U.S. competitiveness in the 21st century. The science centers can contribute significantly to this effort, but they do not have the resources to do everything on their own. NASA should ensure that its science centers cooperate among themselves and with other entities, particularly those supported by the NSF, to develop and implement a strategy for leveraging their EPO efforts to reach the education community.

BOX 6.1 Best Practices for NASA Astronomy Science Centers

Mission Operations

NASA astronomy science centers can best operate the spacecraft and process the resulting data if they

- Have close interaction among scientists, engineers, and programmers. Such interaction is especially important for off-site principal investigator (PI) teams.
- Have research scientists who participate actively in mission operations and in policy decisions.
- Have mission staff knowledgeable about the instrumentation and the satellite in order to provide detailed advice and technical support to the user.
- Provide adequate instrument calibration.
- Provide functional software by the time data first arrive.

Science Operations

NASA astronomy science centers can best support their scientific user communities if they

- Support robust, accessible, well-documented software.
- Use common rather than instrument-specific software across missions when possible.
- Maintain adequate online supporting materials and a help desk with adequate staffing and rapid turnaround.
- Provide user-friendly protocols and software for proposal entry and require minimal technical details for the initial proposal.
- Enable coordinated observations and proposal submission among multiple space- and/or ground-based observatories.
- Co-locate staff to support multiple missions with related scientific objectives.
- Retain key science center staff by providing them with evolving opportunities in either multiple missions or within the host/managing institution.

- Give scientists at science centers guaranteed research time but not guaranteed observation time.
- Have a visiting scientist program.

Data and Archiving

Science centers can best process, store, and disseminate their data if they

- Provide rapid (<24 hr) response to requests for data that have been calibrated and archived.
- Support common analysis software and protocols that can be used by all the science centers.
- Maintain mission expertise at the archive centers for the long-term support of active users.
- Ensure that standards for access to all astronomical data archives are coordinated by an entity such as the National Virtual Observatory and that the infrastructure, including formats and analysis tools, is accessible and sustainable.

Education and Public Outreach

Science centers can best communicate their results to the public if they

- Involve staff scientists and investigators in education and public outreach (EPO) activities.
- Coordinate EPO efforts of smaller missions with EPO systems of the large NASA astronomy science centers.
- Develop classroom resources that
  - — Are designed iteratively through field testing and evaluation in actual classrooms.
  - — Include hands-on activities when possible.
  - — Support standards-based curricula.
  - — Are packaged with protocols for measuring learning effectiveness.
  - — Are accessible and cross-linked so that teachers can easily find them.
  - — Include teacher support (e.g., Web-based teacher guides, training for master teachers).

Appendixes

A

Tabulated Characteristics of the NASA Astronomy Science Centers

CENTERS AND THEIR MISSIONS

The charge to the committee included a request for "a comparative review of current astronomy science centers in terms of the kinds of roles and services that they provide, their size (e.g., budget, staff), the extent to which they utilize centralized or distributed approaches to their architecture, the roles and status of their staff, the nature of their host or governing institution, governance structure, how they were established by NASA (e.g., sole source versus competition)."

In response, the committee collected and compared information on the centers specifically mentioned in the charge: the Chandra X-ray Center (CXC), which services the Chandra X-ray Observatory (CXO); the Space Telescope Science Institute (STScI), which services the Hubble Space Telescope (HST) and is working on the James Webb Space Telescope (JWST) mission; the Spitzer Science Center (SSC), which services the Spitzer Space Telescope (SST); the RXTE guest observer facility (GOF), which services the Rossi X-ray Timing Explorer (RXTE) mission; the XMM–Newton GOF, which provides services for U.S. users of the X-ray Multimirror Mission–Newton (XMM–Newton), a mission of the European Space Agency (ESA) in which NASA participates; and the Michelson Science Center (MSC), which conducts a variety of tasks, most related to optical interferometry, including work for the developing Space Interferometry Mission (SIM). This is not a complete list of NASA astronomy science centers. For example, it does not include the centers that supported the Compton Gamma Ray Observatory, Extreme Ultraviolet Explorer, and the International Ultraviolet Explorer (IUE) when they were operating missions, nor does it include the Far Ultraviolet Spectroscopy Explorer (FUSE), which has a guest observer program. The Wilkinson Microwave Anisotropy Probe mission is not included, although it does support archival research. Other principal investigator (PI) missions such as the Galaxy Evolution Explorer (GALEX), Swift, the Cosmic Hot Interstellar Plasma Spectrometer, and the Submillimeter-Wave Astronomy Satellite were outside the scope of the study. The High Energy Astrophysics Science Archive Research Center (HEASARC) and the Infrared Processing and Analysis Center (IPAC) were considered not on their own but as the umbrella structures for science centers. The list does, however, include the examples—large and small, for existing and developing missions—required for a comparative study. This appendix presents in tabular form the characteristics of these seven centers, as compiled from material supplied by the centers. Tables A.1 and A.2 are organized into operating missions and missions in development.

Space Telescope Science Institute and the Hubble Space Telescope

The STScI was founded in 1981, following a competition, to serve users of the HST. It is located on the campus of the Johns Hopkins University. The Goddard Space Flight Center (GSFC) is a related location, where engineering support and flight operations are conducted. ESA, the European partner in the HST, has a science center at the headquarters of the European Southern Observatory in Garching, Germany, as well as staff at STScI. The governing institution of STScI is the Association of Universities for Research in Astronomy (AURA), a private, not-for-profit consortium of 32 U.S. universities that provides oversight and community input. STScI's operation by AURA, under contract from NASA through the GSFC, gives it a degree of independence from NASA not enjoyed by the science centers operated by the GSFC itself; this arrangement was specifically recommended by an NRC study.[1] STScI was the first of the flagship science centers founded to support major NASA astronomical missions—specifically, the NASA Great Observatories—and its mode of operation has been followed by the large mission science centers that came later.

NASA is planning for 5 more years of HST operations after the planned shuttle servicing mission in late 2007/early 2008. Without this servicing mission, the probable remaining lifetime for scientific operations is about 3 years. The HST archive is expected to continue to serve the international community for many years after science data cease to be acquired. STScI also has been designated by NASA as the science and operations center for JWST, whose development is led by GSFC. This activity is expected to grow in the interval leading up to launch of the JWST, currently planned for 2013.

Chandra X-ray Center

CXC was established in 1991, following a competition, to support users of the CXO. It is located at the Harvard-Smithsonian Center for Astrophysics. The Marshall Space Flight Center holds and oversees the contract for CXC. CXC's governing institution is the Smithsonian Astrophysical Observatory (SAO), a bureau of the Smithsonian Institution. SAO conducts a mix of government and contract and grant-funded work. In principle, and barring a catastrophic failure, the CXO could have a very long lifetime.

Spitzer Science Center

SSC was founded in 1997, without competition but with review of the assignment by the Space Infrared Telescope Facility (SIRTF) science working group, to support users of the SST. It is located at the California Institute of Technology (Caltech) and is a component of the IPAC, an umbrella organization for infrared astronomy that was founded in 1986 to support users of the Infrared Astronomy Satellite. The Jet Propulsion Laboratory (JPL) is a related location where flight operations are conducted; its governing institution is Caltech. The SST has a limited lifetime determined by the cryogens required for cooling the detectors. NASA's Level 1 requirement on mission lifetime is 2.5 years, which has already

[1] National Research Council, 1976, *Institutional Arrangements for the Space Telescope*. Washington, D.C.: National Academy of Sciences.

TABLE A.1 Characteristics of Astronomy Science Centers Associated with Selected Current Missions

Umbrella Organization/Center	CXC	STScI[a]	IPAC/SSC	HEASARC	
Mission	CXO	HST	SST	XMM–Newton[b]	RXTE
NASA mission budget (million $)[c]	61.0	92.0	78.0	9.5	6.0
Center budget (million $),[d] including	53.3	77.6	61.7	7.4	5.9
EPO	2.5	5.0	1.9	0.2	0.1
Grants[e]	11.7	26.5	33.1	5.9	1.9
Total staff (FTE)[f]	238.1	264.7	140.7	7.0	25.7
Flight operations	61.5	155.0	57.2	0.0	16.0
General operations[g]	150.3	28.6	45.2	5.0	8.7
(Amount of total dedicated to research)	(17.0)	(22.0)	(16.6)	(0.7)	(4.9)
Administrative support: management, information technology, grants	12.4	55.2	31.7	1.2	0.7
EPO	13.9	25.9	6.6	0.8	0.3
Number of fellows	13	34	14	0	0
Number of users served (2004)	~900	~1,800	~1,000[h]	320	261
Number of user grants (2004)[i]	196	275	270	130	57
Number of mission-related refereed papers (2004)	250	600	89	360	132
Archive					
Total size (Tb)	2.6	24.9	22.8	0.71	1.4
Annual ingress (Tb)	0.3	4.4	2.5	0.15	1.0
Number of downloads per year	44,000	20,300	100,000[j]	1,100	14,000

NOTES: CXC, Chandra X-ray Center; CXO, Chandra X-ray Observatory; EPO, education and public outreach; FTE, full-time equivalent; HEASARC, High Energy Astrophysics Science Archive Research Center; HST, Hubble Space Telescope; IPAC, Infrared Processing and Analysis Center; RXTE, Rossi X-ray Timing Explorer; SSC, Spitzer Science Center; SST, Spitzer Space Telescope; STScI, Space Telescope Science Institute; XMM–Newton, X-ray Multimirror Mission–Newton.

[a]STScI has a contract to operate the Multimission Archive at Space Telescope Science Institute (MAST), $3 million annually, which is not included in this table or in the budget total shown. The MAST archive contains 10 Tb of data from IUE, GALEX, FUSE, and other missions.

[b]XMM–Newton is a European mission and flight operations are the responsibility of ESA.

[c]The NASA mission budget includes *science and mission operations costs at the science centers and grants to the community* plus: science and mission operations costs at the related NASA centers; industrial contractors; and *PI sustaining engineering.* It does not include new PI-led instrument development, servicing mission costs, or foreign contributions.

[d]The total budget for the science centers themselves; that is, only those items shown in italics in footnote *c*.

[e]The amount shown as grants includes funds granted for theory and/or data analysis to PIs, legacy teams, guest observers, and fellows, as well as the support of the fellowship positions.

[f]Number of total FTE for HST at STScI includes 15 FTE funded by ESA. It does not include indirect staff even though their cost is contained in the total budget. This is done to make a fair comparison with the Chandra and Spitzer centers. The cost for staff with this function (human resources, accounting, purchasing, etc.) is covered by an overhead applied to salaries at the Chandra and Spitzer centers, with the overhead cost contained in their total budget. As a result, these overhead functions do not appear in their staff numbers. It does not include flight operations staff even thought their cost is contained in the total budget. Again, this is done to make a fair comparison with the Chandra and Spitzer centers. At Spitzer and Chandra, flight operations are contracted to JPL and Marshall Space Flight Center, respectively.

[g]Including staff time for research.

[h]The number of users served shown for Spitzer is for 2005 and was derived by counting all PIs, co-investigators, etc., and dividing by three on the assumption that each individual is counted three times on average.

[i]The number of grants listed represents the number of PIs; separate grants made to co-PIs have not been included. The total number of astronomers sharing the support for observing programs is obviously larger than the number of grants.

[j]The table gives the number of observation data sets requested per year. As each download request may contain several observations, this number may be larger, by definition, than those for the other centers.

TABLE A.2 Characteristics of Astronomy Science Centers Associated with Selected Space Missions Under Development

	STScI	IPAC/MSC
Umbrella Organization/Center Mission	JWST	SIM and Other NASA-Funded Activities in Optical Interferometry
Center budget (million $),[a] including	9.4	11.8
EPO		2.7
Grants		2.5
Total staff (FTE)[b]	49.7	41.3
General operations	39.9	39.3
Administrative support: management, information technology, grants	9.7	2.0
EPO	0.1	0.0

NOTES: FTE, full-time equivalent; IPAC, Infrared Processing and Analysis Center; JWST, James Webb Space Telescope; MSC, Michelson Science Center; SIM, Space Interferometry Mission; STScI, Space Telescope Science Institute.

[a]The total budget for the science centers themselves; that is, only science and mission operations costs at the science centers, grants to the community, and PI sustaining engineering.

[b]Number of total FTE does not include indirect staff at MSC even though their cost is contained in the total budget. This is done to make a fair comparison with the other centers. The cost for staff with this function (human resources, accounting, purchasing, etc.) is covered by an overhead applied to salaries at MSC, with the overhead cost contained in the total budget. As a result, these overhead functions do not appear in MSC staff numbers.

been passed, but it is estimated that SST could operate 5 to 6 years from the launch in August 2003. Following that, SSC will continue to support the Spitzer data archive, a community research program with Spitzer archival data, and is currently developing plans for operating the short-wavelength channels of the Infrared Array Camera (3.6 and 4.5 μm) in an extended mission. When the Spitzer extended mission ends, after 2012, IPAC will support the Spitzer data archive.

Rossi X-ray Timing Explorer

The RXTE science center was founded in 1995, without competition. It is located at GSFC, a government organization, which is its governing institution.

X-ray Multimirror Mission–Newton

XMM–Newton, a mission of ESA, was founded in 1997, without competition. The European Space Operations Centre in Darmstadt, Germany, is a related location. The governing institution of the U.S. center is located at GSFC, a government organization.

Space Telescope Science Institute/James Webb Space Telescope

In 1999, NASA determined that technical, budget, and schedule risk in JWST development would be minimized by placing the JWST science and operations center at STScI, to build on the HST heritage and to exploit the numerous synergies with that mission. The center is located on the campus of the Johns Hopkins University. Its governing institution is AURA, a private, not-for-profit research management organization owned by 32 U.S. universities. GSFC is a related location where JWST development is led.

Michelson Science Center

MSC was founded in 2000 as a collaboration between Caltech and JPL to support users of SIM and to serve as the center for NASA's efforts in the detection and characterization of planetary systems. Assigned without competition by NASA Headquarters, SIM will be managed, implemented, and operated by JPL, with science operations at MSC. MSC also conducts other activities supported by NASA: science community development through fellowships, workshops, and conferences; single-dish observing on the Keck Telescope for NASA programs; the Keck Interferometer; the Palomar Interferometer Test Bed; NASA observing programs on the Large Binocular Telescope Interferometer; and archiving of a variety of data sets related to planet finding, including data taken with the High Resolution Echelle Spectrograph on the Keck Telescope. MSC is a component of IPAC. JPL and Caltech jointly provide direction and oversight of MSC, which is located on the campus of Caltech, its governing institution.

CHARACTERISTICS OF THE CENTERS

Tables A.1 and A.2 present information on the astronomy science centers. This information gives their size and an idea of the scope of the mission in terms of budget, staffing, size of the user community, the archive, their education and public outreach (EPO) program, and grant support to users. While the diversity of the science centers makes it difficult to compare them, their broad characteristics become clear. The data come from NASA or from the centers themselves. The amounts of money are in millions of dollars (2005), and personnel are counted as full-time equivalents (FTEs). Archive statistics are given in terabytes of data.

Umbrella Organization/Center and Mission

The tables list the centers by name and also list the umbrella organization to which some centers belong. One center, the STScI, is itself an umbrella organization. Originally established as the science center for the HST, it is now responsible for JWST, the Multimission Archive at the Space Telescope Science Institute (MAST), and other contracts. In all cases the table only gives data for the mission shown.

NASA Budget for Centers

The budget recorded by NASA for the science center of one of its astronomical missions differs from the budget on which the center operates. The NASA amount is what is sent to the NASA field center responsible for the mission. That field center either operates the mission's science center itself or contracts with a third party to operate it. A NASA center spends the difference between the two budget amounts on a variety of activities, which include science and mission operations costs at the center and the costs of industrial contracts. It does not, however, pay for developing the instruments for a PI-led mission nor, in the case of HST, for servicing mission costs. Nor are foreign contributions included.

Center Budget

The amounts shown in the tables are the operating budgets for FY 2005. In all but one case the total reflects the amounts for EPO and grants to the user community, including the costs of fellowship programs.

Total Staff

The tables give total staff in FTEs and break the total into various categories. The different organizational structures of the centers make comparison across these categories problematical, and caution should be exercised in drawing conclusions based on this breakdown. EPO is an exception in that it is an activity that can be reliably identified and broken out, and the numbers shown for EPO are a reasonable indicator of effort.

Fellows

The number of fellows supported in FY 2005 by centers that have fellowship programs is shown. The fellowships can be taken up at any participating institution, so the numbers do not indicate how many fellows are at the science center itself, nor do they indicate the number of postdoctoral fellows who may be present at the science center.

Number of Users Served

As an indicator of the size of the community served by a center, Table A.1 lists the number of individuals, counted once, who were PIs or co-investigators on an approved observing or archive proposal in 2004. This number includes foreign investigators.

Number of User Grants

Table A.1 shows the number of grants to users for data analysis in 2004. Because only PI grants are shown, not grants to co-investigators as well, the numbers here reflect the number of observing programs rather than the total number of people supported, which is greater.

Number of Mission-Related Refereed Papers

Table A.1 gives the number of mission-related publications in refereed journals for the year 2004. Obviously, this number is influenced by how the center defines "mission related." Caution should be exercised in drawing conclusions based on this metric.

Archive

The total size, annual ingress, and number of data requests (downloads) for 2005 are given. The number of downloads shown for CXC has been reduced by ~20 percent, the total requested by a single science data center in China, to more accurately reflect the usage by the broad astronomical community.

B

Statement of Task

Background NASA supports an array of astronomy centers, which are intended to maximize the scientific output and productivity of space astronomy missions by facilitating the scientific community's access to and use of space observatories. Most centers provide a number of supporting roles, which often include some of the following:

- Reviewing observing time or archival data use proposals,
- Scheduling observing time allocations and campaigns,
- Operating the observatory,
- Monitoring and managing scientific instrument and/or spacecraft systems performance,
- Defining and developing analysis software,
- Performing data processing,
- Issuing grants,
- Providing technical assistance for guest observers,
- Developing and managing data archives,
- Facilitating communications between the research community and NASA on behalf of specific space missions, and
- Performing public affairs, outreach, and education activities.

The first such center, the Space Telescope Science Institute (STScI), was put in place in response to the SSB report *Institutional Arrangements for the Space Telescope* (NAS, 1976). Other particularly relevant NRC reports that are likely to have a bearing on the study include *Institutional Arrangements for the Space Telescope: A Mid-Term Review* (NRC, 1985) and *Astronomy and Astrophysics in the New Millennium: An Overview* (NRC, 2002).

In addition to STScI, current centers include the Chandra X-ray Center, Michelson Science Center, RXTE Guest Observer Facility, Spitzer Science Center, and XMM–Newton Guest Observer Facility. Other centers provided science support for the Compton Gamma Ray Observatory, Extreme Ultraviolet Explorer, and International Ultraviolet Explorer when they were operating.

Current centers span a significant range of sizes, from the STScI, which has an annual budget of about $98 million and about 450 staff members, to smaller efforts with budgets ~$10 million and no more than about 20 staff members.

Statement of task The study will include the following tasks:

1. Conduct a comparative review of current astronomy science centers in terms of the kinds of roles and services that they provide, their size (e.g., budget, staff), the extent to which they utilize centralized or distributed approaches to their architecture, the roles and status of their staff, the nature of their host or governing institution, governance structure, how they were established by NASA (e.g., sole source versus competition).
2. Identify best practices and lessons learned from experience to date with NASA astronomy science centers.
3. Assess the questions of whether there are optimum sizes or approaches for science centers, whether there are rational break points in levels of service for centers, and what may be significant advantages or disadvantages for different scales of service.

The study will consider all aspects of centers' service to the astronomy community, including space mission operations planning, data processing and archival, grants to observers and data users, science community communications and advocacy.

The study is not intended to be a performance review of current centers, but it is expected to provide an assessment to serve decision-making with regard to future centers.

C

Biographical Information for Committee Members and Staff

STEVEN R. BOHLEN, *Chair*, is president of Joint Oceanographic Institutions (JOI), a consortium of 29 premier oceanographic research institutions that serves the U.S. scientific community through management of large-scale, global research programs in marine geology, geophysics, and oceanography. Dr. Bohlen graduated from Dartmouth College in 1974 and received a Ph.D. in geochemistry from the University of Michigan in 1979. After 3 years as a postdoctoral research fellow at UCLA, he joined the faculty at the State University of New York at Stony Brook, where he was an assistant and then tenured associate professor in the Department of Earth and Space Sciences. His research focused on the chemical and physical evolution of the Earth's continental lithosphere. In 1988, Dr. Bohlen accepted a research position with the U.S. Geological Survey in Menlo Park, California, and held a joint appointment at Stanford University as a consulting professor. In 1995 he became the associate chief geologist for science at the U.S. Geological Survey in Reston, Virginia, where he was responsible for the health and direction of the research programs of the Geologic Division, including earthquake, volcano, and landslide hazard reduction programs; the global seismographic network; energy and mineral resource assessment; climate change; ecosystems; and coastal and marine geology programs.

ROGER G. BARRY is professor of geography and director of the World Data Center for Glaciology at the Boulder/National Snow and Ice Data Center. He is also on the staff of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado. His major interests are in arctic climate, cryosphere–climate interactions, mountain climate, and climatic change. Dr. Barry is a fellow of the American Geophysical Union and a foreign member of the Russian Academy of Natural Sciences. Dr. Barry has held visiting appointments at several international academic institutions, including the Climatic Research Unit at the University of East Anglia, U.K.; the Institute of Astronomy and Geophysics at the University of Louvain-la-Neuve, Belgium; the Department of Geography, University of Canterbury, Christchurch, New Zealand; and the Department of Biogeography and Geomorphology, Australian National University, Canberra. His NRC service includes membership of the Committee on Climate Data Records from Operational Satellites: Development of a NOAA Satellite Data Utilization

Plan, the Polar Research Board (1987-1991), and the Committee on the Human Dimensions of Global Change (1989-1991). He was also a member of the U.S. delegation to the sixth International Conference on Permafrost in Beijing, China (1993).

STEPHEN S. HOLT is professor of physics at the Franklin W. Olin College of Engineering and professor and director of science at Babson College. He was previously the director of space sciences at NASA's Goddard Space Flight Center. His primary research discipline is high-energy astrophysics. He has been selected to be principal investigator and/or project scientist on eight NASA scientific spacecraft, including joint missions with Germany, Japan, Russia, and the United Kingdom. Dr. Holt has received several significant awards, including the NASA Medal for Exceptional Scientific Achievement on two separate occasions, the NASA Medal for Outstanding Leadership, the NASA Medal for Distinguished Service (NASA's highest award), the John C. Lindsay Memorial Award for Outstanding Science, and the COSPAR Medal for International Scientific Cooperation. He is a fellow of both the American Physical Society and the American Association for the Advancement of Science and has been elected to chair a number of scientific societies, including the High Energy Astrophysics Division of the American Astronomical Society, the Astrophysics Division of the American Physical Society, and the Astrophysics Commission of COSPAR. Dr. Holt has served on numerous national and international committees, including the NRC Committee on Space Astronomy and Astrophysics.

RICHARD A. McCRAY is the George Gamow Distinguished Professor of Astrophysics in the Joint Institute for Laboratory Astrophysics at the University of Colorado at Boulder. He has held visiting positions at the NASA Goddard Space Flight Center (1983), Beijing University and Nanjing University (1987), the Space Telescope Science Institute (1988), Columbia University (1990), and the University of California at Berkeley (1997). Dr. McCray's research is in the theory of the dynamics of interstellar gas, the theory of cosmic x-ray sources, and, most recently, the theory of Supernova 1987A. He is widely regarded as the world leader in theoretical x-ray astronomy. Dr. McCray is a member of the National Academy of Sciences and has extensive NRC experience, most notably from his service on the Space Studies Board (2000-2002) and as co-chair of the Committee on Astronomy and Astrophysics (2000-2002).

ALEXANDER S. SZALAY is the Alumni Centennial Professor in the Department of Physics and Astronomy at Johns Hopkins University. His research interests include the multicolor properties of galaxies; galaxy evolution; the large-scale power spectrum of fluctuations; gravitational lensing; pattern recognition and classification problems; and large, scalable databases. He served on the NRC Panel on Theory and Computation in Astronomy and Astrophysics (1998-2001) and is currently a member of the U.S. National Committee for CODATA. Dr. Szalay also played a leading role in the development of the National Virtual Observatory, an international Web portal allowing astronomers to tap into and search multiple astronomy databases.

PAULA SZKODY is a professor of astronomy at the University of Washington. She is widely known for her work with dwarf novae and magnetic cataclysmic variables (CVs). As a participant in the Sloan Digital Sky Survey, she and her colleagues are currently finding the faintest, lowest mass transfer CVs. Dr. Szkody uses a multiwavelength approach to observational studies of the CVs. She is an active user of the Hubble Space Telescope, Chandra, FUSE, and XMM–Newton satellites as well as APO and ground-based optical facilities around the world. She is a fellow of the AAAS, has served as president of the

International Astronomical Union's Commission 42 on Close Binaries and as a scientific editor of the *Astrophysical Journal,* and is currently editor of *Publications of the Astronomical Society of the Pacific*. Dr. Szkody served on the NRC Task Group on Space Astronomy and Astrophysics (1996-1997).

PAUL VANDEN BOUT is a senior scientist at the National Radio Astronomy Observatory (NRAO). He served as director of the NRAO from 1985 to 2002 and as interim director of the Joint ALMA (Atacama Large Millimeter Array) Office from 2002 to 2003. Before joining the NRAO in 1985, Dr. Vanden Bout was a faculty member at the University of Texas, Austin, where he was head of the millimeter astronomy group in the Department of Astronomy. Prior to that, he was a postdoctoral fellow and faculty member in the Physics Department at Columbia University, where he worked in x-ray astronomy. His current research interest is spectroscopy of star-forming molecular clouds, particularly in distant galaxies. He is a member of the American Astronomical Society, the International Astronomical Union, and the International Radio Science Union and a fellow of the American Physical Society and the American Association for the Advancement of Science. He served as a member of the NRC Committee on Space Astronomy and Astrophysics (1978-1981).

Staff

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Acronyms

2MASS	Two Micron All Sky Survey
ADS	Astrophysics Data System
ALMA	Atacama Large Millimeter Array
APT	Astronomer's Proposal Tool
ASCA	Advanced Satellite for Cosmology and Astrophysics
AURA	Association of Universities for Research in Astronomy
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CLEA	Contemporary Laboratory Experiences in Astronomy
CXC	Chandra X-ray Center
CXO	Chandra X-ray Observatory
EPO	education and public outreach
ESA	European Space Agency
EUVE	Extreme Ultraviolet Explorer
FITS	Flexible Imaging Transport System
FTE	full-time equivalent
FUSE	Far Ultraviolet Spectroscopic Explorer
GALEX	Galaxy Evolution Explorer
GLAST	Gamma-ray Large Area Space Telescope
GOF	guest observer facility
GOODS	Great Observatories Origins Deep Survey
GSFC	Goddard Space Flight Center

HEASARC	High Energy Astrophysics Science Archive Research Center
HOU	Hands-on Universe project
HST	Hubble Space Telescope
IPAC	Infrared Processing and Analysis Center
IRAC	Infrared Array Camera
IRAF	Image Reduction and Analysis Facility
IRAS	Infrared Astronomy Satellite
IRSA	Infrared Science Archive
IUE	International Ultraviolet Explorer
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
MAST	Multimission Archive at Space Telescope Science Institute
MSC	Michelson Science Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NED	NASA/IPAC Extragalactic Database
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSF	National Science Foundation
NSSDC	National Space Science Data Center
NVO	National Virtual Observatory
PI	principal investigator
PROS	Post-reduction Offline Software
ROSAT	Roentgen satellite
RPS	Remote Proposal System
RXTE	Rossi X-ray Timing Explorer
SAO	Smithsonian Astrophysical Observatory
SIM	Space Interferometry Mission
SIRTF	Space Infrared Telescope Facility
SPOT	Spitzer Planning Observation Tool
SSC	Spitzer Science Center
SST	Spitzer Space Telescope
STScI	Space Telescope Science Institute
SWAS	Submillimeter Wave Astronomy Satellite
VO	Virtual Observatory
XMM–Newton	X-ray Multimirror Mission–Newton