Policy Opportunities

S12 - 89
20084
P-18

N91-33029

I. INTRODUCTION

In addition to setting scientific priorities for the discipline, the AASC was charged to assess current policies and practices in the conduct and support of space and ground-based astronomy and to recommend changes that are likely to enhance the productivity of the enterprise. In this Chapter, we consider the relationship and balance between ground-based and space astronomy, strategies for achieving high productivity in both these programs, the support of individual scientists and scientific facilities, international cooperation, the scientific advisory process, and the role of astronomy in education.

In §II we describe the context for our recommendations. In subsequent sections we provide the rationale for our recommendations, the major ones of which are listed below.

The first set of recommendations, discussed in §III, is directed toward the National Science Foundation Astronomy Division. We recommend:

- The NSF should retain primary responsibility for the US ground-based astronomy program, which is a vital component of the nation's overall astronomy effort.
- The budget of the NSF Astronomy Division, in constant dollars, should be doubled during the next 5 years in order to recover ground lost during the past decade, to ensure continued US leadership in ground-based astronomy, and to realize the scientific benefits of the space program.
- NSF-Astronomy should undertake the construction of new facilities *only* in the context of a strategic plan in which the university grants program is adequate to support excellent research programs and the most productive and highest quality observational facilities can be supported adequately. Support for other facilities should be terminated. First call on research funds should be on strengthening the base rather than on building large new facilities.
- The National Optical Astronomy Observatories (NOAO) should provide leadership by building facilities with unique capabilities that will be used by all optical/IR astronomers. In addition, the NOAO should continue to provide access to first-class observing facilities comparable to those at private or university-owned observatories. Whenever possible, the latter mission should be accomplished by cooperation with private and/or state institutions, with emphasis on cost- and technology sharing and the avoidance of duplication of specialized instruments.

The second set of recommendations, discussed in §IV, is directed toward the NASA Space Astrophysics program. We recommend that:

- NASA should carry out the program outlined in the OSSA 5-year Strategic Plan, including full implementation of the Great Observatories program and the deployment of second-generation image-correcting instruments for the Hubble Space Telescope.

- In addition to the 5-year plan, NASA should expand its support of moderate and small programs, implemented by a doubling of the Explorer budget and expansion of the suborbital program.
- NASA should adopt management strategies for the Explorer program with the aim of developing missions faster and at lower cost.
- NASA should support an augmented research and analysis program that is stable and protected against cost overruns of its hardware programs.
- The development of astronomical facilities for the Space Exploration Initiative should follow a logically phased approach. Whenever feasible, the technology development program should include testing through actual astronomical research on the ground, on stratospheric platforms, and/or in earth orbit. The greater expenses of astrophysical observatories on the Moon must be fully justified by the greater scientific return that they are expected to provide.

In §V, we recommend a program for education in astronomy:

- To exploit the unique potential of astronomical and space research to attract young people into scientific and technical careers, astronomers should participate in a broad educational initiative designed to provide more access to the excitement of modern astronomy for students, teachers, and the general public.

Finally, in §VI, we address several other policy issues and recommend that:

- A standing committee of the National Academy of Sciences be established to monitor the overall health of the field and to provide strategic, coordinated advice to all agencies that support research in ground-based and space astronomy.
- Astronomical research will advance most rapidly in a climate of open exchange of information and access to all facilities, foreign and domestic, by the best qualified observers. The agencies should support open access to US facilities and data and should expect other countries to reciprocate.
- We encourage international cooperation on the construction of facilities when each country or entity brings complementary capabilities to the project or when the international nature of the project is uniquely valuable to its performance.
- National and private observatories should formulate policies and make plans for the entry of astronomical data in standard formats into a national archive to enable access by the broad astronomical community. The agencies should encourage these efforts and support their implementation according to scientific merit as determined by peer review.
- NASA and NSF should consider the development oι procedures and facilities to enable the simultaneous multi-wavelength observations of variable celestial sources.

II. THE CONTEXT OF THE RECOMMENDATIONS

The NSF and NASA provide primary support for US research in astronomy and astrophysics. During the 1980's, these agencies have responded to the advice of the previous NAS Astronomy Survey Committee (ASC) report.

The National Science Foundation has implemented, fully or partially, many of the ASC recommendations for new ground-based facilities. For example, construction for the Very Long Baseline Radio Telescope Array (VLBA) is now well-advanced. NSF provided partial support to build new 2 - 4 meter-class telescopes at universities, one of which is already operational, and the NOAO has formed partnerships with private universities to build and operate such telescopes at KPNO and CTIO. NSF financed the construction of a submillimeter telescope on Mauna Kea. The Agency supported several outstanding young astrophysicists through the Presidential Young Investigator program. It provides advanced computing power to astrophysicists through the national supercomputing centers and the national research network.

In addition, the NSF Astronomy Division initiated the solar Global Oscillation Network project and responded to the collapse of the Green Bank radio telescope by funding the construction of a modern fully-steerable 100-m radio telescope. The NSF Division of Polar Programs supported the development of astrophysics programs to exploit the unique advantages of the South Pole.

It is also encouraging that the NSF has improved its budgeting for major projects by setting up a separate project line item within the Division of Mathematical and Physical Sciences.

After the Challenger accident, NASA recognized a crisis in space science and responded by a commitment to do space science for its own sake, independently of the manned program. The Office of Space Science and Applications (OSSA) developed a balanced Five Year Strategic Plan that includes an exciting program for astrophysics research. In this plan, NASA recognizes that: (1) the OSSA Budget should be a stable fraction (20%) of the total NASA budget; (2) much of space science can be done best with expendable launch vehicles; and (3) NASA must provide stable support for a healthy infrastructure of theory, data analysis, and instrument development at universities in order to realize the benefits of its science missions and to ensure the future vitality of space science.

The rich scientific yield of the COBE satellite proves NASA's wisdom in re-structuring that mission for launch with an expendable rocket rather than the Space Shuttle. NASA should avoid using the Shuttle to launch free-flying satellites for astrophysics unless its unique capabilities are *required* for the mission.

NASA has steadfastly supported the Great Observatories Strategy recommended by the ASC Report. The first of these, the Hubble Space Telescope (HST), has been launched, the Gamma Ray Observatory (GRO) will launched in early 1991, the Advanced X-Ray Astronomy Observatory (AXAF) has been started, and the Space Infrared Telescope Facility (SIRTF) has a high priority in NASA's five year strategic plan. The budget for Explorer satellites was increased, and the first-ranked intermediate program, the Far Ultraviolet Spectroscopic Explorer (FUSE), is under development.

Beyond that, the NASA Astrophysics Division launched two astronomical Explorer missions (IRAS and COBE) and sustained a vigorous suborbital program on rockets, balloons, and aircraft. The scientific value of the suborbital program was illustrated by NASA's quick and decisive response to the extraordinary scientific opportunity presented by Supernova 1987A, which yielded irreplaceable data on the infrared and gamma ray emission from this unique event. OSSA initiated a new program for Small Explorers (SMEX). The NASA Astrophysics Division also developed a creative program of international cooperation involving US participation in several European, Japanese, and Soviet astrophysics missions as well as participation by several other countries in NASA missions.

NASA's Astrophysics Division has made plans to strengthen the infrastructure of university science in support of its missions. These include support for individual scientists through the Astrophysics Data Program and data analysis programs of individual missions, and a commitment to make space data available to all qualified scientists. Recognizing that scientific insight often comes from integrating data obtained at different wavelengths, NASA-Astrophysics provides science-oriented funding in addition to mission-oriented funding for data analysis.

It makes sense for NSF and NASA to work together toward the common goal of understanding of astronomical phenomena. NASA's Planetary Division supports the Infrared Telescope Facility on Mauna Kea. NASA has also cooperated with the NSF to upgrade the Arecibo radio telescope of the National Astronomy and Ionosphere Center (NAIC) and the VLA in order to enhance their capabilities for deep space tracking, planetary radar, and astronomical research. NASA and NSF have worked together to distribute advanced detectors, originally developed for space missions, to ground-based observatories, greatly enhancing the power of their optical telescopes.

These activities have been carried out in the face of major obstacles. The NSF Astronomy Division has received insufficient funding to respond fully to the ASC recommendations. NASA's space science programs for the 1980's were set back severely by science funding shortfalls, delays in the Shuttle Program, and the Challenger accident. The success of NSF and NASA in implementing part of the recommended program despite these handicaps is a tribute to the hard work by dedicated people at NSF and NASA. We appreciate their service. We commend both NASA and NSF for relying on the peer review process in making decisions for funding.

We endorse the agencies' practice of using "rotators," research scientists on temporary leave from universities, on agency staff. We encourage universities to recognize and reward such service and call on the AAS Council to encourage members to participate.

The Departments of Defense and Energy have also contributed substantially to astrophysics research and technology development, and we expect this synergism to continue. Between the end of World War II and 1960, DoD support provided the foundation for the great expansion of astronomy that has occurred since then and for our present preeminence. DoD continues to support research in astrometry and optical interferometry, and technology developments in cryogenics, infrared detectors, adaptive optics, fiber optics, and parallel computer architectures. DoE scientists have been leaders in calculations of gravitational collapse, supernova explosions, nucleosynthesis, and stellar opacity, and in observations of cosmic X-ray and gamma ray sources.

The Space Exploration Initiative has the potential to provide new astronomical observing capabilities that can qualitatively improve astronomical resolution and sensitivity. A Presidential Decision of February 16, 1990 enlists the help of the Departments of Defense and Energy in this initiative.

The Smithsonian Institution, through its Astrophysical Observatory, has supported research in astrophysics for a century. The Observatory is now engaged in a broad range of research efforts, including studies of large-scale structure of the universe, high energy phenomena, atomic and molecular interactions, radiative transfer, stellar atmospheres, cosmic masers, molecular clouds, star formation, and the solar system. Facilities include a major optical observatory, available in part to visitors.

The National Institute of Standards and Technology supported measurement and theoretical calculations of atomic and molecular processes that are fundamental to the understanding of many astronomical observations and phenomena.

Although the policies of the 1980's have yielded many successes, our panel has identified several opportunities where the implementation of new policy recommendations would improve the productivity of the enterprise:

- Astrophysics suffers because the ground-based astronomy program is too small to yield full scientific value from the nation's investment in space. There has been a serious decline in the infrastructure of ground-based astronomy, including both the support of existing facilities and of individual researchers. We make recommendations to correct this problem in §III.
- NASA can improve productivity, stimulate inventiveness, and train a new generation of space scientists and managers by devoting more resources to missions of reduced complexity that can be developed and launched within about three years. These and other issues are discussed in §IV.
- The national astrophysics program can attract more talented people into scientific careers. It also can contribute substantially to improving scientific and technical literacy. In §V we give our rationale and present recommendations to accomplish these goals.
- We provide some guidelines for the scientific advisory process, international cooperation, archiving of astronomical data, and multi-wavelength observations, in §VI.

After this Chapter was nearly completed, we learned that the Hubble Space Telescope was launched with a defective mirror that seriously compromises the present ability of the telescope to do the frontier science for which it was designed. Our Panel cannot assess the specific causes for this problem; that task has been assigned to other Committees specifically charged to do so. There are, however, important lessons to be learned from our experience with the HST that are independent of the specific causes of the mirror problem; we discuss them in §IV(g).

III. REVIVING THE NATION'S GROUND-BASED ASTRONOMY PROGRAM

Once a star performer among U.S. science programs, ground-based observational and theoretical astronomy is now imperiled by continuing budget cuts, with consequent decay of major facilities and loss of key staff personnel at national observatories. The cause of this decline is twofold – the NSF basic research budget did not keep pace with the scientific needs of the nation and the relative priority for astronomy within the Foundation declined.

Ground-based observational astronomy and associated theory are the essential core of astronomy. Without adequate support, the U.S. risks losing the fruits of its entire astronomy program, including the space effort. A modest augmentation of the ground-based effort can strongly enhance the total yield of the space program. Astronomy drives technology and science education; it is appreciated and admired by the general public and provides, for many, their only glimpse into what science is all about. Thus, the current crisis of support for ground-based astronomy is a national problem – for astronomy, for scientific efficiency, for science education, and for scientific prestige.

a) Why Ground-based Astronomy?

The number of U.S. ground-oriented observational and theoretical astronomers has doubled since 1970, reflecting the excitement of the subject. Of all recent astronomical papers that refer to observational data, 72% relied mainly on ground-based data, while an overwhelming 83% contained at least some ground-based data. Space observations stimulate ground-based activities rather than replace them. Of the space-oriented papers studied, 39% also utilized ground-based data, and most of these reported new ground-based data acquired specifically to follow up and support the space discoveries. Although these statistics are probably influenced by the lack of launch opportunities for astronomical spacecraft during the 1980's, it is clear that ground-based observations are fundamental to astronomical research. The case for an excellent ground-based observational program is even more compelling in view of the relatively modest cost of ground-based facilities. Clearly, whatever can be done on the ground, should be done on the ground.

Without adequate ground-based follow-up to space observations, America risks losing much of the cream of its space science program. Astronomers in other countries have invested heavily in ground equipment. They can easily obtain data from our open space archives and follow up with superior ground-based facilities. The solution is to augment our own ground-based capabilities with comparatively modest expenditures, to a level appropriate to realize the full potential of the space effort. To fail to do so would be a serious mis-allocation of national resources.

b) The Unique Role of the National Science Foundation in American Astronomy: The Importance of a Strong NSF Program

NSF, the only Federal agency with a mandate to support basic research, has unique responsibilities and abilities. NSF funds many grants and small projects with short lead times and great flexibility. This is especially important for theory, which would become seriously distorted if it were tied too closely to specific missions. NSF should therefore remain the principal custodian of funding for basic theoretical science in the U.S. Averaged over the past decade, the Astronomy Division of the NSF devoted only nine percent of its University budget to theory, a relatively low percentage compared to other Federal offices that support theory.

The NSF peer review process is generally perceived to be fair. The Astronomy Program Directors have a good track record of embracing the priorities in the Astronomy Decade Reviews. However, they lack the resources to do the job properly.

Astronomical research has historically been centered in university departments, the main source of advanced education and professional training. Combining the roles of basic research, training, and education at public and private universities is the unique property of the US scientific research system. Maintenance of this system, which is the envy of other scientifically advanced nations, is a primary responsibility of the NSF. Finally, astronomy stimulates extraordinary popular interest, and is a major asset to the NSF in its mission to cultivate public awareness of science.

c) The Decline in U.S. Ground-based Astronomy

The current crisis follows directly from the long-term funding history. New facilities have been constructed and the number of ground-oriented observational astronomers has doubled since 1970, but the budget (in Consumer Price Index-adjusted dollars) to operate facilities and conduct basic research has not increased in the past twenty years, despite a substantial expansion in the scope of the science. NOAO opened two new 4-m optical telescopes and absorbed the operation of Sacramento Peak Solar Observatory within its declining budget. NRAO opened the VLA, staffed a new site in Socorro, NM, and began to operate the VLBA. At the same time, improvements in astronomical instrumentation and data analysis algorithms have increased the power of optical and radio telescopes greatly. The cost of operating the NAIC was transferred from DARPA to the NSF. The number of visiting observers at all national observatories has tripled in the past twenty years. At the same time, their staffs have declined. To expect efficient operation of a larger program with less staff and smaller budgets is unrealistic, and it shows.

The decline of the budget is illustrated in Table 1. *Corrected for the Consumer Price Index (CPI), the budget has been flat for twenty years. Corrected for the actual cost escalation in technical environments of*

8.5% per year during the decade 1980-1989, the NSF base budget declined in real spending power to only 71%, and the spending per astronomer to 36%, of what they were in 1970.

Construction of new facilities and advanced technology development at national observatories was achieved only through a diversion of resources from other critical areas, resulting in deferred maintenance, and deferred purchase of new equipment. Long-term deleterious consequences of these policies, now apparent, are detailed below.

The specific effects for the University Grants Program and the National Observatories illustrate the impact (all budgetary figures are expressed in real dollars corrected using NSAC [see Table 1] inflation):

University Grants Program (36% of base budget). The NSF is the source of almost all grants to support ground-based observational work. Most astronomers have no alternative funding sources for this work.

- The purchasing power of an average grant fell by more than a factor of two since 1980.
- Available grant funds per U.S. astronomer have been reduced by 1/2 since 1980.
- The number of funded postdoctoral fellows fell by 20% since 1980.
- The success rate of new proposal applicants, mostly young investigators, fell to 10%. Most new applicants have no alternative sources for funding their research programs.
- Many leading researchers had grants delayed, slashed, or cancelled.

National Optical Astronomy Observatories (NOAO) (30% of base budget):

- Staff level was cut by 15% since 1984, 25% since 1979.
- Budget was cut by 21% since 1984.
- One heavily utilized telescope was permanently closed, more closures are under review.
- Two-thirds of observing requests are now rejected for lack of facilities.
- Travel support has been suspended for visiting observers. Many observers now pay travel out of their own pockets for lack of NSF grants (even to CTIO in Chile).
- The Advanced Projects Group at NOAO was closed for lack of funds. Group leader was hired away by European Southern Observatory to build world's largest telescope (ESO VLT project). NOAO lost its leadership in optical telescope construction and advanced optics.
- Other countries now dominate large-telescope construction. Seven large telescopes were built abroad since 1975. In the same period NSF funds built 1/2 of one telescope in the U.S. Relative decline in forefront optical and electronic technology is comparable.

National Radio Astronomy Observatory (NRAO) (27% of the current base budget):

- Operations staff was cut by 15% in last 5 years.
- Operations budget was cut by 30% over last 5 years.
- Leadership in millimeter astronomy – developed by the US – was lost to Europeans and Japanese. No major new telescopes were built, despite an elegant proposal.
- Deferred maintenance, such as the VLA track system, requires one-time funding of several million dollars.
- Cannot operate VLA at full capability or exploit new image processing techniques for lack of modern receivers and adequate computers – despite excellent peer reviews.
- Operations funds for the VLBA are ramping up at only half the rate required to put antennae into service.
- The world-famous NRAO technical group is threatened due to low salaries and low morale. Director says, "If the core technical team disbands, the Observatory has no future."

National Astronomy and Ionosphere Center (NAIC) (7% of base budget):

- Staff was cut by 10% in last five years, 24% since 1979.
- Budget was cut by 35% since 1984.
- Decaying scientific equipment, some of it 25 years old.

Table 1. Long-Term History of the NSF Astronomy Base Budget[1]

Year	1970	1980	1989
Actual-year dollars	$23.8M	$52.2M	$77.4M
CPI adjusted[2]	1.00[3]	1.03	1.06
NSAC inflation adjusted[4]	1.00[3]	1.03	0.71
Per U.S. astronomer (CPI)[5]	1.00[3]	0.76	0.55
Per U.S. astronomer (NSAC)[6]	1.00[3]	0.76	0.36
Rel. to total NSF budget[7]	1.00[3]	0.96	0.80
Rel. to MPS budget[8]	—	1.00[8]	0.78
Rel. to U.S. GNP[9]	1.00[3]	0.81	0.63

[1] The NSF base budget includes the university grants program and funds for the operation and maintenance of the National Observatories. New construction is omitted.

[2] Adjusted for increases in the Consumer Price Index.

[3] Set to 1.00 in 1970.

[4] Adjusted for "technology inflation", as estimated by the Nuclear Science Advisory Committee subcommittee on inflation. We have applied a correction of 4.6% per year to this figure to the period 1980-1989. No adjustment has been applied to the period 1970-1980, for which no comparable data are available.

[5] Adjusted using the increase in total AAS membership and CPI inflation.

[6] Same as the previous row, but with NSAC inflation assumed.

[7] Adjusted for increase in the total NSF budget.

[8] Adjusted for increase in the Mathematical and Physical Sciences budget (set to 1.00 in 1980, since MPS did not exist in 1970).

[9] Adjusted for increase in U.S. national GNP. Shows NSF astronomy as a fraction of national effort.

d) Augmenting the NSF Astronomy Budget

Funding for ground-based astronomy has fallen so far below par that a concerted effort of restoration is required. The figures in Table 1 mandate, at minimum, a doubling of the NSF base budget for astronomy during the next five years. Astronomy has not shared in the growth of the NSF budget for many years. Given the situation described above and the spectacular continuing advances possible in this field, a period of above average increases is warranted.

e) The Role of NOAO in Ground-based Night-time Astronomical Research

Astronomers hold conflicting views of the role of NOAO in ground-based, nighttime optical astronomy. On the one hand, the observatories were established and continue to be used to provide night-time facilities that are comparable in aperture to those run by universities or private institutions to which access is usually restricted by affiliation. On the other hand, many astronomers believe that NOAO should focus its efforts on providing unique facilities, such as the European VLT (Very Large Telescope).

About 20 percent of NOAO users come from groups planning to construct their own 8-m and 10-m telescopes. The remaining 80 percent typically do not have access to such facilities, and most do not have access even to 1-4 meter class telescopes. Given this situation, there is substantial resistance among the latter group to expenditure of NOAO's budget for building more ambitious, state-of-the-art telescopes if doing so precludes the continued operation and enhancement of the existing telescopes.

For long-lived facilities like telescopes, operation costs over their lifetimes exceed initial capital costs. As larger and more modern facilities become more common, smaller and aging telescopes appear less attractive and cost-effective. Changes in scientific emphasis also favor larger aperture.

As guidelines towards definition of an achievable mission that will serve a wider segment of the U.S. astronomical community, we recommend:

- That NOAO further reduce its support of those telescopes with relatively low oversubscription rates, seeking arrangements, whenever possible, to transfer them to private institutions.
- The NOAO should endeavor to increase the time it can make available on 4-m class telescopes by seeking more partnership arrangements like the several efficient cost-sharing arrangements with university consortia that it has recently undertaken.
- NSF-astronomy and NOAO should establish provisions for trading or purchasing telescope time from private and university groups operating 8-m and 10-m class telescopes and smaller special-purpose telescopes in order to ensure that the full range of observing facilities is available to the whole community. Astronomy in the U.S. would be well served by a cooperative interdependency of the private and public sector.
- By adding 8-m telescopes, NOAO will continue to fulfill its mission of providing access to front-line facilities to all astronomers independent of institutional affiliation. The construction and operation of 8-m telescopes and a 4-m telescope dedicated to fiber optics spectroscopy, and technology development for optical and infrared interferometry, are also important steps for development of a technical base upon which even more ambitious, unique facilities will be built.

The development of *unique* facilities, which are distinguished either by scale or function, is a crucial step by which NOAO can broaden its support of the entire astronomical community. To maintain leadership in optical astronomy, NOAO needs the *active* involvement of the nation's leading astronomers, including those with access to private 4-m, 8-m and 10-m telescopes. They must be involved in the definition of NOAO projects and their implementation, and most importantly, they must *use* these facilities. The presently planned 8-m telescopes for NOAO are an important step along the way. A larger world-class, unique facility for optical astronomy will be needed to ensure scientific leadership by NOAO and to exploit fully the U.S. advantage of combining powerful resources in both the private and public sector.

- NOAO cannot be the site for all of the necessary technological innovation, but it can play a vital role as a clearinghouse for such technology. To this end, NOAO should encourage outside partnerships in detector and instrument development.

The health and success of U.S. optical astronomy has been based on a combination of a strong *national* observatory together with *non-federal* funding for private and university facilities that is unique in the world. A partnership that enhances the strengths of these two elements will ensure continued U.S. leadership in optical astronomy.

IV. A VIGOROUS PROGRAM OF SPACE ASTROPHYSICS

NASA's agenda of unfinished astrophysics missions remains substantial. For example, the HST needs repair, SIRTF has not yet been started, and AXAF and most of the Explorer missions approved during the 1970's and 80's will not be launched until the late 1990's.

OSSA's five year strategic plan incorporates this unfinished agenda. We endorse this plan without reservation. In doing so, we recognize that its completion establishes NASA's strategy for most astrophysics missions to be launched until the late 1990's. Therefore, our recommendations cannot affect this plan in a major way. They should, however, affect the process by which NASA will select and implement astrophysics missions to be started during this decade and beyond.

a) An Enhanced Explorer Program

We recommend that NASA develop a more vigorous program of missions with reduced complexity and shorter times from inception to completion. At present, the funding is weighted toward large missions costing more than $300 M, such as HST, GRO, and AXAF. Averaged over 1984 - 1989, the fraction of NASA astrophysics project funding devoted to large missions was 73%, compared to 12% for moderate ($100 - 300 M) missions and 15% for small (< $100 M) missions, including rockets, balloons, and aircraft.

Large missions such as the Great Observatories have revolutionary capabilities that cannot be matched by moderate and small missions. The latter, however, can add a dimension to NASA's space science program that is vital and cannot be provided by the large missions: the ability to deploy new instrumental technology into space on a timescale of a few years. The prospect of rapid access to space is a strong driver of innovation. This opportunity attracts and permits the training of talented young instrumentalists, engineers, and project managers who are essential, not only for the health and future of NASA's space science programs, but also for the nation's future technical competitiveness. Yet, only two Explorer missions devoted to astronomy were launched during the period 1980-89.

There are many good ideas for scientific payloads for small and moderate missions to make critical scientific observations that cannot be done with any other planned mission. For example, a 1988 NASA solicitation yielded 27 proposals for Delta-class Explorer missions for astrophysics, 7 of which were ranked with highest ("category 1") scientific priority, and a 1989 solicitation yielded 17 proposals for Scout Class Small Explorers (SMEX) for astrophysics, 3 of which were ranked category 1. However, it was only possible for NASA to select one mission for development from each of these competitions owing to the constraints of the Explorer budget. Moreover, some of the most innovative instruments developed by U.S. space scientists are now being flown first on foreign spacecraft for lack of NASA launch opportunities.

The present level of the Explorer budget is approximately \$60 M/yr for Delta-class missions and \$30 M/yr for SMEX. Assuming optimistically that Delta-class missions will cost \$120 M each and SMEX \$30 M each, the Explorer budget will then permit one Delta-class mission every two years and one SMEX per year. That is approximately the necessary rate for a robust Explorer program for astrophysics alone, but the current Explorer budget must also support missions for several other disciplines of space science. Thus, a doubling of the Explorer budget is the minimum needed to maintain a vigorous program of astrophysics Explorer missions assuming that half the budget will be devoted to astrophysics missions.

Presently, the scientific opportunities for small and moderate Explorer missions are constrained by NASA's lack of an expendable rocket with payload intermediate between those of the Scouts and Deltas. Important new opportunities for powerful but relatively inexpensive astrophysics missions will appear when OSSA procures such a vehicle.

b) Costs and Management of Small and Moderate Missions

Even with a doubling of the Explorer budget, we will be able to achieve rapid and steady access to space only by holding mission development to cost and schedule. The productivity of the Explorer program will be maximized by having more frequent cost- and schedule-constrained missions rather than by maximizing the scientific performance of each individual mission. We have seen examples, such as the Japanese *ASTRO* program, where this strategy has enabled a robust program of X-ray astronomy missions launched at regular intervals.

Cost and schedule control begins with the Explorer selection process. NASA has begun to introduce incentives by supporting a greater number of missions for the definition phase (Phase A) and then conducting a second competition to select missions for development (Phases B,C,D). To ensure that this strategy is successful, NASA should also: (1) include mission costs and their impact on the Explorer program as criteria of the peer review process in both the Phase A and Phase B competitions; (2) hold the management teams to their budgets, *even if it becomes necessary to scale down performance specifications.*

It is vital for cost containment that missions have *all* critical technologies under control before they are selected for development. To meet this requirement, NASA should invest adequately in technology development in its Research and Analysis program and in Phase A. If so, we see no reason that mission development should require more than three years from the beginning of Phase B to launch.

To achieve an optimum result within budget and schedule, the project management team must be able to trade off scientific performance and cost, and take risks if necessary. In order to enable this process, NASA should: (1) vest full authority, including control over budget, staff, and procurement in a project management team consisting of the Project Manager and the Principal Scientific Investigator; and (2) provide full funding as planned to support the master schedule.

There are necessary risks to such a strategy. If the project management team fails to meet milestones or exceeds costs, NASA must decide whether to stretch the schedule and augment the funding or to cancel the mission. Such decisions should be based on a careful assessment of the options and their impact on the overall Explorer program, with advice from the scientific community. The gains – in technical development, management experience and program discipline – may outweigh the losses if an occasional mission is cancelled.

c) A Renewed Partnership with Universities and Industry

If moderate and small missions can be launched at a healthy rate, we think that NASA can achieve a more productive overall small/moderate mission program by involving project management and systems engineering at universities working with private industry, and/or NASA centers. Universities have unique advantages for attracting and training people for careers in engineering and management as well as in basic science. By providing opportunities to work on all aspects of space missions at universities, NASA can help provide a healthy supply of technically proficient and talented people, not only for its own needs but for the nation in general.

The time is ripe for a more vigorous partnership between NASA, universities, and the aerospace industry in space science projects. The aerospace industry has a rich reservoir of management and technical expertise for the building of space hardware, and space science could benefit greatly if more of this capacity became available as a result of decreased demand for defense systems.

We therefore recommend that NASA carry out its Explorer program in the context of a "mixed economy," in which some missions are developed by NASA centers and others are developed by management teams from universities working with private industry. Within such an economy, NASA should compare cost and productivity and seek an optimum mix.

d) Astrophysics within the Space Exploration Initiative

NASA's Space Exploration initiative presents exciting prospects for astronomical observations on the lunar surface. There are, however, great uncertainties about the technical and logistical infrastructure to support such facilities, the timescale for their development, and the cost. It is prudent for astrophysicists to work with NASA to understand better the opportunities and problems of doing astronomy on the Moon. NASA should develop the required technology in logical phases.

To ensure that the required technology is effective, NASA should, whenever feasible, test it on the ground, on suborbital platforms, and/or in Earth orbit. The requirement to produce actual scientific results in these tests introduces a technical rigor to the program that paper studies cannot provide. Further, the investment required to test the scientific and technical systems on the ground or in Earth orbit is relatively small. It is the best way to ensure maximum return from the much greater investment that will be required to install and operate an observatory on the Moon. Since the development phase of this initiative will be long, the opportunity to do scientific observations during this phase would help to attract and train the highly talented scientists whose energies and skills would be essential to the success of this initiative.

e) A Vigorous Program of Suborbital and Airborne Research

Our recommendation that a greater fraction of NASA's resources be allocated to Explorers is motivated by several important goals: (1) the training of young astronomers and instrumentalists; (2) fast turn-around and frequent opportunities for testing and developing new instrumentation and techniques; and (3) improved cost-risk-benefit ratios to foster innovation. All of these desiderata are met extremely effectively by NASA's suborbital programs of rocket, balloon, and airborne astronomical research.

These suborbital platforms play a unique and critical role as test-beds for new instruments. Because of the nature and operating procedures of these programs, astronomers have excellent access for adjustments and modifications to their instruments. In the airborne program, as epitomized by the highly successful Kuiper Airborne Observatory (KAO), most groups have continuous access to their instruments during operation and can make minor adjustments even *during* a research flight. More significant adjustments and modifications can be made between flights on the KAO, or between launch opportunities for rockets and balloons.

This "hands-on" mode of operation also provides a special opportunity for the training of young instrumentalists. The pay-off provided by the opportunity to participate directly in instrument development is apparent from the established track records of suborbital programs. Examples include: the explosive growth in our understanding of the interstellar medium due to the development of ultraviolet spectroscopy, initiated through the rocket program; the development of powerful new gamma ray telescopes through the balloon program; and the invaluable role of the KAO in the professional development of most currently active and prominent researchers in infrared and submillimeter astronomy. A recent survey of participants in the KAO program, which provides flight opportunities for about two dozen research groups per year, has shown that the KAO has supported the Ph.D. research of about 40 scientists who are currently active in these fields.

The ready access to the instruments in the suborbital program leads to a balance of costs, risks, and benefits that is very different from that for instruments on spacecraft. The high degree of reliability required for instruments on spacecraft drives up their cost, precluding frequent launch opportunities. As a result, high-risk but innovative instrumental development is inhibited. In contrast, suborbital platforms are ideal for trying out truly innovative but risky ideas, since the price of a single failure is relatively minor. Thus the suborbital programs are an essential component of a well-balanced strategy for instrumental and scientific progress. Furthermore, the intrinsic flexibility in scheduling the suborbital platforms allows short-term redirection of these facilities to take advantage of targets of opportunity, such as bright comets or SN 1987A.

For all of these reasons, we strongly endorse NASA's suborbital research program, and support vigorous expansion of this program in areas where the scientific and instrumental opportunities are well-defined and offer the potential of high rewards.

f) The NASA Research and Analysis Programs

NASA's research and analysis program supports activities that are essential to its space science program, including:

- research and development of new instruments for its flight programs
- data analysis for specific flight programs and panchromatic analysis of archival data sets.
- theoretical investigations needed to interpret data from space missions, to enable better planning of future missions, and to gain a deeper understanding of the universe.

NASA has recognized that the support of these activities is inadequate and plans to increase its support of these activities through the Astrophysics Data Program, the Astrophysical Theory Program, the Hubble Fellowship Program, the Long-Term Space Analysis Program, and individual research grants. NASA must sustain this commitment and protect the planned growth of these programs in order to ensure a stable and strong infrastructure for its space science programs.

These programs are also NASA's primary mechanism for support of space science research at universities. Funding through grants to individuals and small groups at universities has proved to be a highly productive way to support scientific research and is NASA's *only* way to train the next generation of space scientists. Larger research centers also have essential roles to play in supporting instrument development, data analysis, and theory.

NASA's research and analysis programs gain strength through a healthy competition among universities and centers for limited resources. In order to ensure that the programs have maximum productivity and to maintain a healthy balance between funding of individual scientists and larger centers, it is important that all programs for support of research and analysis be reviewed periodically, with community input.

g) The Problems of the Hubble Space Telescope

Although this Panel cannot assess the causes of the defective mirror on the HST, we wish to make a few comments here that are independent of the findings of those committees charged to investigate that problem.

First, the HST should eventually be able to fulfill its role as the centerpiece of NASA's Space Astrophysics research program for the 1990s. Except for the mirror, the telescope and all its instruments are working well. It can be used now to do frontier science, and it can be restored to nearly full capability provided that its focal plane instruments can be replaced by new ones containing correcting optics. NASA should make these replacements as soon as it can do so according to priorities established by its scientific advisory committees.

Second, the HST mirror problem does not lead us to modify the major recommendations of this Chapter; indeed, the problems of the HST only reinforce some of the conclusions that we had already reached.

Third, the HST mirror problem reminds us that no space science program can be immune to failure. When the fraction of resources concentrated in missions of large scale and long development times becomes too large, the space science program becomes brittle and unforgiving of failure and cost-overruns. Failure can be tolerated least in the most expensive missions; that fact drives their development costs higher. NASA should have a space science program that is more resilient to the occasional failures that will occur. That is one of several reasons why our Panel has urged NASA to devote a greater fraction of its resources to missions of small and moderate size.

Fourth, the most serious problems of the HST project (not only the mirror problem) can be traced to errors that were made in its early stages. At that time there was inadequate involvement of scientists in technical oversight and decision-making. NASA should require the scientists who have most at stake in a space mission to assume a greater share of the responsibility and accountability for technical decisions. Participation in oversight committees is not enough; the scientists must be involved at the working level. In particular, scientists with personal commitments to the ultimate uses of a mission must participate in the design and implementation of systems tests that verify the correct performance of all aspects of the mission before launch, and NASA must support such tests. In order to ensure this involvement, NASA must provide scientists with adequate resources for technical support, especially during the critical early development stages.

Fifth, the development of the HST was troubled by diffusion of authority and responsibility among different centers and the lack of a prime contractor. Moreover, the long delays in development contributed to a lack of continuity in key management, scientific, and technical personnel. To minimize risk in its large space projects, NASA should vest authority and accountability in a tight management team including the principal scientists led by a single individual of renown and ability who has direct oversight and responsibility for the scientific success of the mission.

Finally, we wish to emphasize that NASA has learned many of these lessons and is already applying them to the management of future Great Observatories such as AXAF and SIRTF. If NASA continues in this path, these missions should not be susceptible to the most serious problems that have troubled the HST project.

V. AN EDUCATION INITIATIVE IN ASTRONOMY

In his 1990 State of the Union Address, President Bush declared, "By the year 2000, U.S. students must be first in the world in math and science achievement." Astronomers have much to contribute to this high national goal. Here we recommend a strategy for astronomers to increase their current contributions to science education and national scientific literacy.

Education in astronomy has several distinct but overlapping goals. One is the training of astrophysicists. Modern astrophysics research requires people of high talent trained in diverse specializations. The supply of newly-trained astrophysicists that existed in the 1970's and early 80's is shrinking rapidly, while at the same time the research opportunities and demands for trained personnel are growing. Therefore, we must attract and train people in the field with renewed vigor. This is especially true for women and minorities, who remain severely underrepresented in the profession.

A second goal is to contribute to the broader national pool of professional scientists and engineers. Many physicists, chemists, engineers, and computer scientists are drawn into their careers through an initial interest in astronomy, and many people trained as astrophysicists pursue careers in other areas of science and technology.

A third goal is to help raise scientific literacy in the nation. For this goal, astronomy has a number of advantages, such as: the intrinsic fascination of the cosmos; astronomy's central role in the history of physical science; the accessibility, diversity and universality of astronomical concepts and techniques; the glamour of the space program; and the vitality of amateur astronomy.

The nation's colleges and universities are doing a good job of training scientists. However, too few students enter college with adequate scientific literacy or the intention of pursuing scientific careers. A serious attempt to address the three goals stated above must emphasize the pre-college (K - 12) years, and that is the focus of this section.

Astronomers are involved in many aspects of science education. In colleges and universities throughout the nation, introductory astronomy courses have high enrollments and provide the main exposure to physical science for many undergraduates. Teaching undergraduate and graduate courses in astronomy and astrophysics is the primary educational commitment for many of the nation's research astronomers. Astronomers also make contributions beyond the college classroom. Most college and university departments welcome the general public to their telescopes and research facilities in public "open nights." Astronomers write articles for popular science journals, they contribute to educational television programs, and they speak at local schools, museums and planetariums, amateur astronomy clubs, and other civic groups.

Astronomers also support more organized efforts for science education beyond the university. The American Astronomical Society (AAS) conducts workshops for local schoolteachers and public lectures at its semiannual meetings and supports expenses for astronomers to visit colleges and universities that do not have astronomers on their faculties to give lectures in classrooms and public lectures for the local communities. The Astronomical Society of the Pacific (ASP) conducts meetings for amateur astronomers and publishes "Mercury," a non-technical journal of astronomy that is written for the public, educators, and amateur astronomers as well as "The Universe in the Classroom," a newsletter of wide circulation. The Harvard-Smithsonian Center for Astrophysics, with NSF support, is developing a year-long "hands-on" high school course that uses examples from astronomy to teach fundamental principles of physics and mathematics. Astronomers, sponsored by the NSF Education Division, have conducted summer workshops for schoolteachers at national observatories and universities. The International Astronomical Union's Teaching Commission provides liaison with astronomy educators around the world.

The enthusiastic response to these activities reveals a great unmet public demand for more exposure to the fruits of modern astronomical research. How can the nation's astronomers meet this demand? There are millions of schoolchildren who need more exposure to astronomy, but only a few thousand professional astronomers, most of whom are already heavily committed to college teaching and research. In fashioning a response to this challenge, we must identify programs that will give high leverage to the limited human resources that we can provide.

A coordinated educational initiative in astronomy should be funded by the educational directorates of the respective agencies, at a level commensurate with the national priority of education, in order to establish a stable interface whereby researchers can provide their resources to the nation's professional educators. This initiative should be guided by three principles: (1) engage the nation's teachers to multiply the astronomers' efforts; (2) make the program highly visible in order to attract the most talented teachers and students; and (3) stress affirmative action.

Several specific strategies consistent with these guidelines have been described in the document "An Educational Initiative in Astronomy" [R. Brown, ed., published by the Space Telescope Science Institute, 1990]. They include, among other ideas:

- Expand summer programs and workshops at universities and national research centers for in-service training of science teachers. These workshops provide the best opportunities for science teachers to gain direct experience with modern astronomical research and to make ongoing contacts with astronomers who are committed to improving science education. The workshops will be particularly effective if they can attract those master teachers who are involved in the development of curriculum materials and the training of other teachers.
- Expand the educational programs of the AAS and ASP. The agencies responsible for funding public education should be responsive to proposals for in-service training of teachers and the development of curriculum materials.
- Increase astronomer participation in textbook and curriculum development at the K-12 levels (astronomers are already heavily involved in the writing of college textbooks). Involvement in commercial endeavors may also generate additional resources and ensure wide dissemination of the products. Professional astronomers should also participate in school or state evaluation and adoption procedures.
- Adapt innovative technologies for use in schools. For example, CD-ROM data bases and image processing programs for the analysis of astronomical data on personal computers can give students the opportunity to become familiar with modern computer technology while they explore the sky in all its wavelength bands.
- Develop special programs for gifted students. High-visibility prestige programs not only help to identify and recruit the future leaders of astronomy, but also send a message to young people that a career in science can be as feasible and rewarding as a career in, say, law or professional sports. We recommend that each state identify one or two outstanding high school students as State Fellows in Astronomy. The students will serve as paid interns at one of the major national or private observatories and will participate as assistants in the active research of the professional staff.
- Recognize and reward astronomers for their contributions to education. The community can encourage

astronomers to contribute to an educational initiative by increasing the reward structure. For example, the AAS can establish awards for contributions to education, science writing, and public service, and universities can reward their faculty for improving public education as well as for their teaching and research.

We have two recommendations for these strategies to be realized in a coherent educational initiative. First, in order to bring the excitement of NASA's space science programs into the nation's classrooms, NASA should provide support to the education initiative that is complementary to the support provided by the NSF education directorate. Second, offices for implementing a major part of the educational initiative should be established at centers operating national research facilities. Such offices should act as clearinghouses for the dissemination of information and curriculum materials, sponsor workshops, and coordinate the State Fellowship program. We recommend that NSF and NASA each establish such an office at one of their research centers and consider establishing additional offices, depending on experience and demand.

VI. OTHER POLICY ISSUES

a) Science Advice to the Government Regarding Astronomy and Astrophysics

NASA and NSF, the agencies providing primary support for research in astronomy and astrophysics, already have in place advisory committees of leading scientists. The National Science Foundation has an Advisory Committee for Astronomical Sciences (ACAST) that reports to NSF management, and NASA has a number of Management and Operations Working Groups (MOWG's) and Astrophysics and Solar System Exploration Subcommittees that report to the Astrophysics Division and Solar System Exploration Division managers and their Directors, respectively. In addition, NASA benefits from advice from the NAS Space Studies Board and its subcommittees for astrophysics (CSAA), planetary and lunar exploration (COMPLEX), and solar-terrestrial physics (CSSP/CSTR). These committees are appropriate entities for advising the agencies on scientific priorities.

However, we believe that astronomy would benefit from an independent standing broad-based Astrophysics Strategic Advisory Committee of the NAS (here called ASAC), constituted of leading scientists from every major sector of astronomical and astrophysical research, including those supported by NSF, NASA, other agencies, private observatories, and industrial research labs. The ASAC should monitor the overall health of the field and provide strategic advice regarding how to maintain a balanced program of astronomy and astrophysics within the guidelines of this Report. The ASAC should not provide continuing tactical advice to the agencies regarding scientific priorities within their purview; that role properly belongs to the ACAST and the MOWG's. Nor should it review or revise the plan presented in the AASC report, which is the result of an extensive effort by a large fraction of the astronomical community.

There are important roles for the ASAC that no other advisory committee can play. One is to provide advice on the global issues in astrophysics research to all agencies to maximize the scientific and educational benefits by working together and with the private sector. Another role is to advise the agencies, the Congress, and the Executive Branch how to achieve the scientific objectives of the decade plan when unforeseen circumstances arise. Examples of such circumstances might be new technical opportunities, failure of a major facility, opportunities for international cooperation, or changes in the budgetary picture beyond the assumptions of the AASC plan. Finally, to have one broad-based standing committee of distinguished astrophysicists may prove especially useful when consideration is given to programs involving more than one agency.

b) International Cooperation and Competition

Research in astronomy and astrophysics has always been an international enterprise. Important astronomical research programs are now being carried out by many nations. Several nations and groups of nations have built and are planning to build research facilities with capabilities that are unmatched in the U.S. The vitality of research in the field, therefore, depends on healthy international cooperation and competition.

The most productive kind of international cooperation occurs when individual scientists exchange knowledge and share facilities to solve specific scientific problems. The scientific programs of all nations flourish when scientists can freely exchange data and technical knowledge and when qualified scientists of any nationality have access to unique facilities throughout the world. Such exchange is essential for effective international cooperation in the construction of instruments and facilities. The United States has and should continue to set a standard for open scientific research that is exemplary to the world. We commend NASA and NSF for opening the competition for observing time on the Hubble Space Telescope and on the National Radio Observatories to qualified observers from all nations. In turn, the United States should expect that other countries will foster an equally open scientific atmosphere.

International cooperation is also fostered by a vigorous program of scientific exchange through workshops and visiting scientist programs, and by opening educational and employment opportunities to highly qualified foreigners. This is another area in which the U.S. has been world leader, and in which it has benefitted greatly by attracting outstanding scientists from all nations, many of whom choose to remain in the U.S. and become citizens. We recommend that this be enhanced by removing the restrictions to US nationals from fellowship and other employment opportunities. The Immigration and Naturalization Service can also help by removing obstacles to permanent employment for highly talented foreign scientists.

International cooperation in building major facilities is appropriate when the nature of the project is inherently international, when the project combines complementary capabilities that exist in different nations, or when the project is too complex or costly for individual nations. Examples which meet these criteria are the Global Oscillation Network for studying Solar seismology, intercontinental radio interferometry, several space missions, and, possibly, a permanent manned observatory on the moon.

However, international cooperation can become complicated when more than one country is involved in the construction and operation of major facilities. In those cases guidelines are needed to manage the greater administrative complexity, costs, and delays that can arise from the need to coordinate technical interfaces and independent national bureaucracies. Before undertaking such projects, the agencies, together with their scientific advisory committees, should scrutinize them carefully to determine whether the benefits of the cooperation outweigh the costs. For some projects, independent supra-national entities like CERN or ESO may be appropriate. In many cases, science will advance more rapidly if nations elect to build unique specialized facilities on their own rather than collaborating with other nations. Such a strategy becomes most attractive if nations agree to make their unique facilities available to qualified scientists from any nation.

c) Archiving and Distribution of Astronomical Data

Modern astronomical instruments produce multidimensional data of enormous size and complexity, which often do not reveal all of their secrets and subtleties upon initial examination. Upon further examination, data archives can yield answers to questions that the original observers may never have considered. Archival research can be especially productive when data taken at different times or wavelength bands are compared. Investigators can also use archival data to study large volume-limited or flux-limited samples of objects and to assess the feasibility and merit of proposed observing programs. Rapid advances in technology now allow us to store very large astronomical databases and to make them readily available to qualified researchers. We expect archival research to become an increasingly important part of astrophysics, as more investigators gain access to and become familiar with these data sets and the powerful workstations and software for analyzing them.

Public access after an appropriate proprietary period can maximize the scientific return on data obtained at great effort and cost. It also encourages the timely publication of the results of observing programs. We commend the steps that have already been taken. All data obtained from NASA space programs are available to the public after a proprietary period of typically one year. NASA has made a major commitment to and financial investment in preparing calibrated archives of most data obtained with its space-borne instruments. The Agency has also developed an on-line central directory to identify and locate the data, and it has supported the dissemination and analysis of these data through the peer-reviewed Astrophysics Data Program. The Space Telescope Science Institute has developed an archive system to make data from the HST available to all qualified scientists. The NRAO has created a raw data archive of all VLA data with public access after 18 months. The NOAO and NRAO have established the standard

FITS formats for data transfer and have provided the IRAF and AIPS data analysis tools to the community. The IAU has adopted and is working to extend the FITS standards, and NASA has established a FITS Support Office.

The development and preparation of archives is often expensive, especially when efforts are undertaken to produce data products for distribution, i.e., data that have been processed to remove instrumental signatures, calibrated, and reduced to simplify access by users. Techniques and algorithms for processing archival data sets continue to evolve as scientists gain a better understanding of the instrument and the data set. Therefore, it may be better to defer processing the entire data set.

It may soon become practical and worthwhile to incorporate many kinds of astronomical data, including ground-based data, into an international network that is accessible to all qualified researchers. To make this happen the NSF and NASA should work together and with scientific agencies of other nations to provide the resources and standards, with the active involvement of the community. Because the choices for storage media and means of handling and accessing data are evolving rapidly, and costs are still unclear, it is prudent to adopt a measured approach toward this goal.

As a first step, NOAO and other ground-based observatories with Federal support should formulate and implement policies for archiving newly generated data, building on the experience of efforts that are already underway. The policies should address questions such as: when does an instrument become sufficiently standard for the data to be archived routinely; what formats should be used; what documentation is required for its calibration and interpretation; what are the most cost-effective means for storing and distributing the data; and for what period should the data remain proprietary.

We also urge private observatories to formulate and implement their own policies for archiving and distributing their data. The NSF should respond to requests from private observatories for capital expenses associated with the establishment of archives with the advice of peer review. Since the production of archived data can add scientific value to observing projects, observatories and individual investigators should be requested to describe their plans and performance in archiving data in proposals for research support.

NASA and NSF should work together to create a unified on-line directory to provide access to all archived ground-based and space data. NASA should provide information, assistance, and coordination for software and connectivity to the ground-based National and private Observatories. The National Observatories should provide catalogs of archived data for the NASA Astrophysics Directory Service.

Subsequent steps toward an international archive of astronomical data may include facilities to make archived data themselves accessible through electronic networks, the incorporation of previously archived data into modern storage media, the production of archives of processed data products, and the critical evaluation of astronomical data bases.

The agencies should support the steps described above on a case-by-case basis when the scientific benefits of the project justify the cost. Such decisions should always be based on a peer-reviewed assessment of the scientific merit compared to other activities, such as instrument development and observing, that compete for the same scarce resources.

The ultimate form of processed data is its publication in a refereed professional journal. It may become feasible and desirable to include such data in an international archive base. The journals should adopt policies to enable retrieval of archival data described in submitted papers, as is done in some other research fields.

d) Multi-wavelength Observations of Variable Sources

Throughout the history of astronomy, observations of the time variation of celestial objects have yielded exciting new discoveries and fundamental insights into the nature of cosmic systems. Today, the ability to observe variable celestial sources in all wavelength bands of the electromagnetic spectrum has revealed entirely new phenomena, such as active galactic nuclei, X-ray binaries, and gamma ray burst sources, the interpretation of which continue to challenge astrophysicists. Analyses of the time variability of such systems at various wavelength bands have provided the most basic clues to their nature.

The revolution in modern astronomy has been driven largely by the ability to compare observations of celestial sources in different wavelength bands, and this certainly must be true for variable sources as well as for steady ones. Indeed, simultaneous observations at different wavelengths can yield fundamental information about variable sources that can be obtained in no other way. However, the task of coordinating such observations with telescopes on the ground and in space presents logistical problems that are always difficult and often technically impossible with current organizational procedures and available instrumentation.

For these reasons, we recommend that NASA and NSF pay particular attention to finding ways to seize the scientific opportunities of multi-wavelength observations of variable sources. NASA should consider the development of spacecraft dedicated to multi-wavelength observations of variable sources, and NASA and NSF should work together to establish a dedicated capability for providing simultaneous ground-based optical, infrared, and radio observations of sources that are observed by NASA spacecraft.

BENEFITS TO THE NATION FROM ASTRONOMY AND ASTROPHYSICS PANEL

VIRGINIA TRIMBLE, University of California, Irvine; University of Maryland, *Chairman*
JOHN N. BAHCALL, Institute for Advanced Study, *Vice-Chair*

ERIC CHAISSON, Space Telescope Science Institute
ARTHUR CODE, University of Wisconsin, Madison
EDWARD K. CONKLIN, FORTH, Inc.
JOHN COWAN, University of Oklahoma
ALEXANDER DALGARNO, Harvard-Smithsonian Center for Astrophysics
FRANK DRAKE, University of California, Santa Cruz
REBECCA ELSON, Harvard-Smithsonian Center for Astrophysics
GEORGE FIELD, Harvard University
ANDREW FRAKNOI, Astronomical Society of the Pacific
HERBERT FRIEDMAN, Naval Research Laboratory
JOHN S. GALLAGHER, AURA
JESSE GREENSTEIN, California Institute of Technology
HERBERT GURSKY, Naval Research Laboratory
STEPHEN MARAN, NASA Goddard Space Flight Center
PHILIP MORRISON, Massachusetts Institute of Technology
CATHERINE A. PILACHOWSKI, Kitt Peak National Observatory
PHILIP SADLER, Harvard-Smithsonian Center for Astrophysics
CARL SAGAN, Cornell University
PHILIP SCHWARTZ, Naval Research Laboratory
STEVEN SHORE, NASA Goddard Space Flight Center
ALEXANDER G. SMITH, University of Florida
HARLAN SMITH, University of Texas, Austin
MICHAEL S. TURNER, Fermi National Accelerator Laboratory
PAUL A. VANDEN BOUT, National Radio Astronomy Observatory
GART WESTERHOUT, U.S. Naval Observatory
JAMES WESTPHAL, California Institute of Technology
R. STEPHEN WHITE, University of California, Riverside
ALBERT WHITFORD, University of California, Santa Cruz