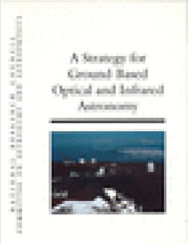

A Strategy for Ground-Based Optical and Infrared Astronomy

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A Strategy for Ground-Based Optical and Infrared Astronomy

Panel on Ground-Based Optical and Infrared Astronomy

Committee on Astronomy and Astrophysics
Board on Physics and Astronomy
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Front Cover: The summit of Mauna Kea. Owing to atmospheric conditions at an altitude of 4.2 km, this observatory is generally regarded as one of the finest sites known for OIR astronomy observations and hosts many of the world's greatest telescopes. Seen in the foreground (left to right) are the 3.8-meter United Kingdom Infrared Telescope, the University of Hawaii 2.2-meter Telescope, a small dome soon to be demolished to allow construction of the Gemini North 8-meter Telescope, and the 3.6-meter Canada-France-Hawaii Telescope. Beyond them are the domes of Japan's 8-meter-class Subaru Telescope, the two sister 10-meter telescopes of the W.M. Keck Observatory, and the 3-meter NASA Infrared Telescope Facility. The summit of Haleakala, Maui, where the Phillips Laboratory is constructing a 3.7-meter telescope, is seen in the background. (Courtesy of the University of Hawaii Institute for Astronomy.)

Back Cover: The Cerro Tololo Inter-American Observatory. Cerro Pachon, site of the 8-meter Gemini South Telescope, is on the skyline, some 12 km distant. (Courtesy of National Optical Astronomy Observatories.)

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Preface

In November 1993, Hugh Van Horn, director of the Division of Astronomical Sciences of the National Science Foundation (NSF), met with the Committee on Astronomy and Astrophysics (CAA) of the National Research Council (NRC) to seek advice regarding NSF's strategy for supporting ground-based optical and infrared astronomy (hereafter, OIR astronomy). In response, the CAA recommended to the NRC Board on Physics and Astronomy (BPA) that the NRC establish a panel of the CAA, the Panel on Ground-Based Optical and Infrared Astronomy (OIR Panel), to prepare this report.

After consultation with the CAA and other members of the astronomical community, the CAA nominated a list of members for the OIR Panel. The proposed panel was approved by the Board on Physics and Astronomy and appointed by the NRC chair. In addition to the regular members, the OIR Panel enjoyed the active participation of liaison members from the CAA, the BPA, the NSF Physics and Astronomy Advisory Committee, and a consultant from the National Optical Astronomy Observatories (NOAO).

In preparing this report, the OIR Panel met three times. At the first meeting, which took place in Tucson, Arizona, on February 24-26, 1994, the panel heard detailed presentations regarding the budget, staffing, and operations of the NOAO, and it also heard presentations regarding the operations of the Steward Observatory of the University of Arizona. An open forum was held to listen to opinions and advice from Tucson astronomers. At the second meeting, which took place in Washington, D.C., on April 21-22, 1994, the panel held discussions with NSF and the National Aeronautics and Space Administration program managers and representatives of the Association of Universities for Research in Astronomy (AURA, the management contractor for the NOAO). At the final meeting, which took place in Minneapolis from May 30 to June 2, 1994 (held concurrently with the summer meeting of the American Astronomical Society (AAS)), the panel held an open forum to discuss the issues with interested AAS members. The panel also met with members of the Optical, Infrared, and Submillimeter/Meter Strategic Review Panel (the OIM panel) from the United Kingdom (which had a similar charge from the U.K. Science and Engineering Research Council) and representatives of the National Research Council of Canada.

In addition to attending these meetings, members of the OIR Panel visited the Canada-France-Hawaii Observatory, the Sacramento Peak Observatory, Cerro Tololo Inter-American Observatory, and several independent observatories and made a return trip to NOAO to examine its budget and staffing in detail. The panel maintained an open forum on an electronic bulletin board, which elicited a lively debate and many thoughtful and provocative comments. The panel sent a questionnaire to directors of independent observatories requesting detailed information about facilities and operating costs. On July 11, 1994, the chair of the OIR Panel attended a meeting of directors of independent observatories to discuss possible recommendations and the most effective ways to implement them.

With the benefit of these extensive interactions with the astronomy community, the NOAO, the NSF, and other concerned parties, the OIR Panel was able to reach a consensus on a strategy for ground-based optical and infrared astronomy that yields the best scientific return for the NSF investment in the field. This report describes the panel's recommended strategy and the information that the panel used in formulating it.

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A Strategy for Ground-Based Optical and Infrared Astronomy

EXECUTIVE SUMMARY

Astronomy occupies a special place in the research portfolio of this country. Understanding the cosmos is one of the oldest intellectual goals of humanity, and the discoveries of astronomers clearly excite the imagination of the public at large. From primary schools to universities, from planetaria to features in the media, astronomy offers numerous opportunities to improve the scientific literacy of this nation, and astronomers are increasingly engaged in these educational activities.

Although for many people astronomy is a clear example of one of the noblest of basic research activities, it is often less recognized that it can and does contribute to other national goals. In particular, its research activities depend on and contribute to the applied development of sophisticated sensors, an essential enabling technology for many scientific fields and for the defense, medical, and commercial sectors.

Modern astronomical facilities, and their sophisticated instrumentation, utilizing state-of-the-art detectors, computing resources, and optical design, are expensive. Astronomers are fortunate that the Congress has authorized the construction of numerous major national facilities. National ground-based astronomical facilities are supported primarily by the National Science Foundation (NSF), both in the construction and operations phases. The two 8-meter telescopes of the international Gemini 8-M Telescopes Project (IGP), in which the United States is a 50% partner, are currently under construction and will be completed by the end of the decade. Considerable investment (more than $250 M in the past decade) in large telescopes has also been made with nonfederal support, such that private observatories now provide 81% of the total telescope area (and 76% of the net diameter) available to U.S. astronomers. Still, roughly half of U.S. astronomers must rely entirely on the National Optical Astronomy Observatories (NOAO) for access to telescopes, and nearly all rely on NOAO facilities for some aspects of their work.

The Panel on Ground-Based Optical and Infrared Astronomy was convened to determine whether the strategic balance of support by the NSF for all of optical and infrared (OIR) astronomy should be adjusted as these giant new telescopes come on line. In particular, the panel was asked to articulate a new mission for NOAO. In doing so, the panel had to address several complex questions. What is the best role for NOAO in U.S. participation in the IGP? How can the unique resources of both private and NOAO facilities best be deployed? What priorities and strategies should be pursued, recognizing that NSF resources for OIR astronomy will probably be severely constrained?

The panel believes that first priority must be given to the development of unique telescopes and instrumentation that advance technology and provide resources of national scope. The Gemini telescopes, the large telescopes at the Cerro Tololo Inter-American Observatory (CTIO), and the Advanced Technologies and Instrumentation (ATI) program of the NSF's Division of Astronomical Sciences are clearly in this category.

The panel finds that the case for increased OIR funding is strong within NSF for operating the Gemini telescopes. However, it is necessary to face the possibility that NSF funding of OIR astronomy will remain level in real dollars for some time. In this eventuality, the panel recommends that the proper instrumentation and operation of the Gemini telescopes should have first priority. The panel also affirms the high priority for the ATI program, which was recommended by the Astronomy and Astrophysics Survey Committee (AASC) report (*The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991).

The panel concludes that, with level funding, major reductions in NOAO operations would be required to meet the priorities stated above. In this constrained situation the Tucson scientific, administrative, and technical services support would have to be scaled back very substantially. The level of support and convenience offered to observers would have to be reduced, and it is very likely that the smaller telescopes at the Kitt Peak National Observatory (KPNO) would need to be closed or privatized. Moreover, to reduce operations costs, the 4-meter Kitt Peak telescope would have to be operated with fewer instruments and used primarily for wide-field or near-infrared applications. In this case, a large number of astronomers whose only access to front-line research tools is through NOAO telescopes would be unable to carry out their research and U.S. science would suffer.

The panel has identified a strategy that might alleviate such problems and, at the same time, better utilize the very large recent expenditure by the private sector in the construction of new telescopes. Specifically, the panel recommends the initiation of a new program at a modest level within the NSF for instrumentation of the privately operated telescopes in exchange for national access. In a constrained budgetary scenario, such funds would, of necessity, come from existing NSF OIR astronomy activities, including the existing ATI program. Even with this new plan, some 1200 observer nights would be lost, approximately 40% of the present use by the U.S. astronomy community at NOAO nighttime facilities.

The above plan is the best that the panel can envision under a flat-budget scenario. But the panel finds the costs in human, educational, and scientific terms to be unacceptably high. In view of the major capital investments in the Gemini telescopes and other major new telescopes, the panel recommends a second strategy, contingent on the availability of additional funds. **Specifically, the panel recommends that $5.5 M/year be added to the NSF astronomy budget for international Gemini project operations**. If this recommendation is implemented along with the proposed new instrumentation plan, it would allow for far more efficient utilization of existing telescopes. It would still be necessary to slim down the Kitt Peak/Tucson operations, but the consequences for the U.S. astronomy community would not be as draconian as they would be under the first strategy alone.

The panel recommends that a third strategy be pursued, if further funds are available. In this strategy, the NSF astronomy budget would be supplemented by $10 M/year. The first $5.5 M would be used as above for Gemini operations, and the balance would be used to support an augmented program for facility instrumentation grants. Independent observatories would be able to compete for these grants, which would be awarded strictly on the basis of scientific merit, but for which cost sharing, in the form of open access to the astronomical community at large, would be a requirement. Such a program would enable full utilization of the enormous investment in both federal and nonfederal capital in OIR telescopes.

The panel recognizes that when new, state-of-the-art facilities are brought on line, older facilities must be retired. All of the options outlined above include such painful downsizing. In the draconian, flat-budget scenario, the community would lose truly first-rate instruments, but even in the optimal plan, major economies in operations would still be required.

I. INTRODUCTION

The charge to the Panel on Ground-Based Optical and Infrared Astronomy was as follows:

1. Assess the context in which optical and infrared astronomy will be pursued in the coming decade, including existing and planned instruments worldwide, NASA missions, and likely technological developments. This examination must consider the appropriate mission for the National Optical Astronomy Observatories (NOAO); the most effective use of National Science Foundation (NSF) funds for support of facilities, instrument development, and research; and how best to structure our efforts to meet the challenges of the next decade.

2. Within this context, evaluate the mission of the NOAO and define its optimal role (including both nighttime and solar activities) relative to that of other government facilities and optical and infrared astronomy (OIR) university observatories and research departments. This evaluation will take into account both the research and educational roles of the organizations.

3. Suggest and evaluate alternative strategies designed to optimize progress in the field, taking into account the funding available from various federal and nonfederal sources and projections for the future. Give advice for strategies and priorities within OIR astronomy in light of the expectation that the NSF resources available for these programs will be severely constrained in the coming decade.

The OIR Panel was concerned about the reference to solar activities at NOAO in item 2 of the charge. Since the National Solar Observatories (NSO) at NOAO constitute a major part of the national infrastructure for solar physics, the panel was concerned that recommendations regarding NSO might have a major impact on the national strategy for solar research. The OIR Panel did not have the expertise or resources to evaluate this impact properly. Therefore, the chairs of the Committee on Astronomy and Astrophysics and the OIR Panel discussed this issue with Hugh Van Horn of the NSF and reached the understanding that the OIR Panel was expected not to make major recommendations regarding solar facilities, but only to point out the potential impact on solar physics that its recommendations for NOAO might have.

The strategy recommended is intended generally to follow the recommendations of the 1991 NRC report of the Astronomy and Astrophysics Survey Committee, *The Decade of Discovery in Astronomy and Astrophysics* (hereafter, the AASC report; National Academy Press, Washington, D.C.), taking into account developments that have occurred since that report was written.

The goal of the recommended strategy must be to achieve the best science from the NSF investment in OIR astronomy. The total U.S. investment in astronomy includes the capital investment and operating funds from federal, state, and private sources that support the NOAO and many independent observatories as well as the pool of talented astronomers who use these facilities. These astronomers, most of whom teach at colleges and universities, not only advance our knowledge of the universe and the frontiers of technology required to gain this knowledge, but also impart their knowledge and skills to a much greater number of students and to the public.

As the panel describes in Sections II and III, the infrastructure of OIR astronomy is complex and the scientific opportunities are enormous. The major share of NSF funding of OIR astronomy goes to the support of the NOAO, and the greatest current federal capital investment in OIR astronomy is the U.S. share (50%) of the international Gemini telescopes currently under construction. Therefore, strategic advice for NOAO and for NOAO's role in the international Gemini 8-M Telescopes

Project (IGP) is a vital element of a national strategy for OIR astronomy. These issues are addressed in Section IV.

Astronomy enjoys a unique place among the physical sciences in that most of the OIR telescopes in the United States, including the largest ones, were built and are operated with private and state funds (see Section II). Thus, to optimize the scientific return of the NSF investment in OIR astronomy, it is necessary to consider a strategy to provide instrumentation for the independent observatories that own these telescopes. A recommended strategy, which includes a provision for national access to these facilities, is presented in Section V.

The panel interpreted the reference to severely constrained resources in item 3 of the charge as a mandate to consider a scenario in which the NSF annual funding of OIR astronomy would have zero growth for the remainder of the decade (in constant 1994 dollars). In this scenario, options would be very limited, and drastic cuts would be necessary.

However, in view of the major capital investment in astronomy from both federal and private sources, and substantial growth in the number of astronomers, the panel considered scenarios in which the NSF base budget for OIR astronomy would be increased during the coming decade by an amount comparable to that required to support Gemini operations. Such an increase would enable the United States to realize fully the enormous scientific potential of the nation's telescopes.

II. THE STATUS OF OIR ASTRONOMY

The AASC Report

The panel first summarizes briefly the recommendations of the AASC report regarding OIR astronomy and the new developments that have occurred since that report was written.

Substantial progress has been made toward achieving the AASC report's recommendations for new facilities in OIR astronomy. For major new ground-based facilities, the first-priority recommendation was for an infrared-optimized 8-meter telescope on Mauna Kea in Hawaii, and the third-priority recommendation was for a Southern Hemisphere 8-meter telescope. (The second priority was for the Millimeter Array.) The NSF responded to these recommendations through a commitment to support 50% of the international Gemini project. Two 8-meter Gemini telescopes are currently under construction; Gemini North (Plate 1) is scheduled to be fully operational in 2000, and Gemini South in 2003.

For moderate ground-based facilities, the first-priority recommendation of the AASC report was to develop adaptive optics facilities to reduce image distortion by atmospheric turbulence. The NSF has responded to this recommendation by increasing substantially its funding of adaptive optics instrumentation. This effort enjoys major contributions from the Department of Defense, which has undertaken to declassify its advanced technology for adaptive optics, and from the Department of Energy. These agencies support very promising programs in laser guide star technology at the Air Force Phillips Laboratory and the Lawrence Livermore National Laboratory, respectively. The potential scientific yield of adaptive optics technology is enormous. Most of the work to develop and deploy this technology remains to be done; but, as the recent infrared images of the impact of comet Shoemaker-Levy 9 with Jupiter demonstrate, astronomers are already beginning to realize the benefits.

The AASC report's second-priority recommendation for moderate ground-based facilities was for the development of facilities and technology for OIR interferometry. The NSF has responded to this recommendation by increasing its support of technology development for this area. The twin 10-meter Keck telescopes on Mauna Kea, the first of which is now operational and the second of which is currently under construction, will provide a major new facility for OIR interferometry.

The AASC report's third-priority recommendation for moderate ground-based facilities was for the construction of several new 4-meter-class telescopes, supported insofar as possible through a combination of federal, state, and private funds. Substantial progress has been achieved toward this goal with the successful completion of the 3.5-meter ARC telescope at Apache Point, New Mexico, operated by a consortium of state and private institutions and funded partially by the NSF, and the 3.5-meter Wisconsin-Indiana-Yale-NOAO (WIYN) telescope at Kitt Peak National Observatory (KPNO), constructed and operated by a consortium of private and state universities and the NOAO. These excellent telescopes are demonstrating the high scientific performance enabled by new technologies and the financial efficiency of cost-sharing arrangements. More such telescopes are needed, however, most urgently in the Southern Hemisphere.

The AASC report's highest-priority recommendation for ground-based astronomy was not for new facilities, however. It was for the "strengthening of the infrastructure for research, that is, increased support for individual research grants and for the maintenance and refurbishment of existing frontier equipment at the national observatories" (pp. 12-13). In particular, the AASC report recommended that "the NSF should include appropriate financial provision for operation of any new telescope in the plan for that facility," and that "individual research grants be increased to an adequate and stable fraction of the NSF's total operations budget for astronomy. In order to gather and analyze the large amounts of data that will become available with new instrumentation, to allow young researchers to take advantage of the new opportunities for discovery, and to restore support for theoretical astrophysics, the individual grants budget should be increased by $10 million per year" (pp. 13-14).

The NSF Division of Astronomical Sciences has not yet been able to implement fully this paramount recommendation of the AASC report. Moreover, the NSF will find it impossible to address this recommendation or the remaining recommendations for new facilities without an increase in the net funding for astronomy. For example, sufficient funds for the support of the infrastructure of other unique facilities, such as the National Radio Astronomy Observatory's (NRAO) Very Long Baseline Array (VLBA) and Very Large Array (VLA), have not materialized, and these instruments are currently operating in a less than optimal fashion.

A major problem for the NSF is to identify the funds required to operate the U.S. share of the IGP without encroaching on individual research grants or impacting the operations of other important facilities. To do this in a constrained budget scenario will require a further focusing of priorities and resources at NOAO. While NOAO might achieve further efficiencies, certain telescope-instrument combinations would probably have to be closed if NOAO were required to absorb the full cost of the U.S. share of Gemini operations. Furthermore, NOAO's ability to develop new instruments and telescopes and to meet the observing needs of the nation's astronomers would be seriously impaired by such a requirement.

Current Resources for OIR Astronomy

The NSF Astronomy Budget

Figure 1 illustrates the distribution of the NSF Division of Astronomical Sciences 1994 funding (total is approximately $105 M, excluding the $17 M construction costs of the IGP). The dark shaded area represents support of radio astronomy, through the NRAO, the National Astronomy and Ionosphere Center (NAIC) at Arecibo, Puerto Rico, and the independent radio observatories. The hatched "other" portion of the grants program supports primarily individual research grants in theoretical and computational astrophysics and in radio, solar, and planetary astronomy. (Of course, many individual investigations are also supported by NSF through grants to observatories.) The white segment of Figure 1 represents support primarily for OIR astronomy, including grants to individual investigators, development grants from the Advanced

Technologies and Instrumentation (ATI) program, and the OIR part of NOAO. The black segment of Figure 1 represents support of solar astronomy through the NSO and the Global Oscillation Network Group (GONG) project.

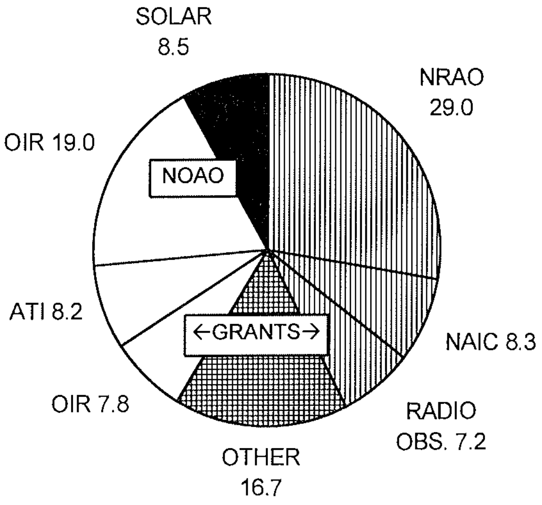

Figure 1. Distribution of NSF Division of Astronomical Sciences 1994 funding ($M; total is approximately $105 M).

Figure 2 shows the history of funding of astronomy research by the NSF in the decade from 1985 to 1994. The net funding (in constant 1994 millions of dollars, corrected for inflation) decreased by about 5% from 1985 to 1990, then increased to a maximum in 1992 of about $118 M (excluding Gemini construction), or about $130 M (including Gemini), and has decreased thereafter. The funding of astronomy, as a fraction of the total NSF Mathematical and Physical Sciences Directorate budget, has decreased from 19.3% in 1984 to 17.2% in 1994, excluding major capital construction projects such as Gemini. Including them, the fraction has decreased from 19.3% to 18.4% during the same decade.

Some redistribution of funding within the NSF Division of Astronomical Sciences budget is evident in Figure 2. The rapid decrease in the NRAO budget after 1992 may be attributed to the termination of funding for construction of the VLBA. Excluding VLBA construction, the NRAO operating budget increased by about 23%, from $23.6 M in 1985 to $29.0 M in 1994. The NOAO budget, excluding Gemini construction but including the GONG project, decreased by about 10%, from $30.5 M in 1985 to $27.5 M in 1994. The funding of grants to individual investigators decreased by approximately 18%, from $25.8 M in 1985 to $21.1 M in 1993, but was restored in 1994 to $25.0 M, 3% less than the 1985 level. The two most significant qualitative changes are the increase by a factor 3.5 of the budget for the ATI program, from approximately $2.5 M in 1985 to $8.7 M in 1994, and the construction budget for the international Gemini project.

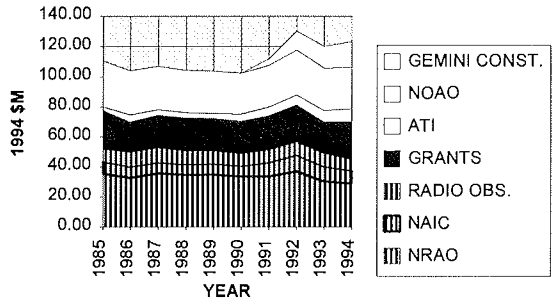

Figure 2. History of funding of NSF Division of Astronomical Sciences from 1985 to 1994. Funding primarily for radio astronomy, including NRAO, NAIC, and the independent radio observatories, is shown with a vertical striped pattern. The NRAO wedge includes funds for construction of the VLBA but not the $75 M funding appropriated by Congress in 1989 for construction of the Green Bank telescope. The NAIC wedge includes funds for the Arecibo telescope upgrade. Funding primarily for OIR astronomy, including the ATI program, NOAO (including solar astronomy), and Gemini construction, is shown as white. Funding of grants to individual investigators, including grants for OIR astronomy but excluding grants for the ATI program and the independent radio observatories, is shown as black.

As noted by the AASC report, the shortage of funding to support research by individual investigators has become acute. This remains true despite the fact that the NSF grants program was restored in 1994 to approximately the 1985 level, because the number of astronomers (measured either by the number of members of the American Astronomical Society or by the number of papers published in the *Astrophysical Journal* and the *Astronomical Journal*) has increased by approximately 40% during the same decade. (Much of this growth can be attributed to rapid growth of NASA programs in space astrophysics.) Astronomy is a growing science, and that has resulted in keener competition, both for research grants and for access to facilities at the national observatories.

The Gemini Project

National Science Foundation funding for the U.S. commitment of $88 M to support 50% of the costs to build the two 8-meter Gemini telescopes (including an initial complement of instruments) commenced in 1991. The U.S. funding profile for Gemini construction is front-loaded, and the obligation will be met with the final U.S. payment of $41 M in 1995. But then, the NSF is committed to pay the IGP 50% of the Gemini operations costs, including instrument upgrades. Figure 3 shows the NSF commitment for 50% of IGP operations; the planned funding profile begins in 1997 and will rise to a steady-state annual rate of $5.5 M by 2003, when Gemini South becomes fully operational. **The need to identify the source of funds for international Gemini operations is the main problem for NSF to solve, in order that U.S. OIR astronomy can realize the scientific yield of its investment in the two telescopes.**

The IGP is intended to support only the management, operations, facilities, and instrumentation development for the telescopes themselves. Each participating nation is expected to provide for the research needs of its own astronomers who will use the Gemini telescopes, including travel, data archiving and distribution, and limited support for instrumentation development. The NOAO is planning to redirect its internal resources to support these activities through the U.S. Gemini Project Office (USGPO) and has estimated that the cost to do so will rise to approximately $2.5 M by 2003. With level funding, NOAO can support U.S. scientific access to Gemini only by reducing support of other activities that it currently supports.

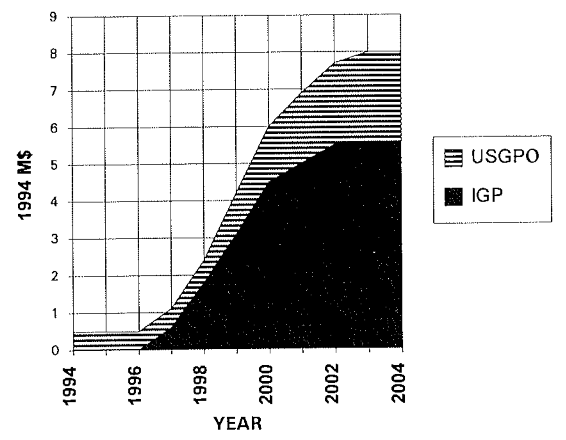

Figure 3. U.S. funding of Gemini operations, showing the U.S. 50% commitment for operations of the Gemini telescopes through the IGP and also the cost estimated by NOAO for the USGPO to support U.S. scientific access.

NOAO

NOAO maintains two nighttime OIR sites: Kitt Peak and Cerro Tololo. Kitt Peak is a reasonably dark site in an area with strong light pollution laws. It has good seeing characteristics, judging by the recent successes of the Michigan-Dartmouth-Massachusetts Institute of Technology (MDM) 2.5-meter telescope and the WIYN telescope. Cerro Tololo has superb seeing characteristics, judging from the site survey work, although the current telescopes do not deliver optimal images. Cerro Tololo (see back cover) is a superb photometric site and very dark. Work on controlling light pollution has begun.

Table 1. NOAO Telescopes and Oversubscription Rates

Telescope	Focal Ratios	Nights Scheduled Feb. 1994-Jan. 1995	Oversubscription Rate by Nights Feb. 1994-Jan. 1995 (dark/bright)
Kitt Peak National Observatory			
4-m	2.7/8/15	278	3.0/2.0
3.5-m WIYN	6.9		
2.1-m	7.5/15	286	2.5/2.0
1.3-m	15	260	1.5
0.9-m	7.5/13.5	274	2.0/1.9
0.9-m Coudé Feed	31	258	1.2
0.6/0.9-m Schmidt	3.5	131	1.9
Cerro Tololo Inter-American Observatory			
4-m	2.7/8/15	298	2.6/2.7
1.5-m	7.5/13.5/30	332	1.4/2.4
1.0-m	10	223	0.9/2.1
0.9-m	13.5	307	1.6/1.0
0.6/0.9-m Schmidt	3.5	191	1.3

Table 1 lists the NOAO telescopes. At both sites, the premier 4-meter telescopes are moderately wide-field (45 arc minutes) Ritchey-Chrétien reflectors. At Kitt Peak, an f/15 secondary is used to optimize infrared capabilities and achieve commonality with the 2.1- and 1.3-meter telescopes. The new 3.5-meter WIYN telescope on Kitt Peak will provide wide fields, up to 1 degree for the multiobject spectrometry port and 0.5 degree for the WIYN port. The WIYN telescope has already delivered images at the 0.4" level. The Schmidt telescopes at KPNO and Cerro Tololo Inter-American Observatory (CTIO) are university-owned, with the observing time shared. They are both capable of 5-degree fields (but limited at the moment to 1 degree at KPNO with a 2048 × 2048 charge-coupled device (CCD) and at CTIO to less than that with a 1024 × 1024 CCD). At CTIO the 1.0-meter telescope is shared with Yale University and the 0.6-meter telescope (dedicated to single-channel photometry) is shared with Lowell Observatory. All the telescopes with apertures of 1 meter or less have very restricted instrumentation to provide for efficient operation.

KPNO hosts approximately 600 astronomer-visits per year for use of its telescopes and CTIO approximately 200 per year. Table 1 lists the scheduling and oversubscription rates (nights requested/nights scheduled) in 1994 for all NOAO telescopes. It shows that in 1994 the smaller (2.1 m or less) telescopes at KPNO provided some 1200 observer-nights, or approximately 43% of all NOAO observing time.

Helmut Abt's studies* on the cost-effectiveness of telescopes, the research done at NOAO, and institutional productivities all show that NOAO has been scientifically productive. Moreover, many major astronomical discoveries have been made with NOAO telescopes. A few of the many examples include the Infrared Tully-Fisher relationship, the Bootes Void, the Lyman alpha forest, the first gravitational lens, and the flat rotation curves of spiral galaxies.

The competitive access to NOAO telescopes is crucial to the nation's science. The panel examined NSF grant funding over the three-year period from 1991 to 1993 to identify the dollar amounts that have gone to researchers at institutions with guaranteed access to telescopes with apertures of 2 meters and larger, and those at institutions lacking such facilities. Omitting astrometric programs and solar astronomy, 55% of the funding in OIR observational research has gone to those with "perennial access." The remaining 45% has gone to those with "annual competitive access," and who presumably rely absolutely on NOAO for the capability to carry out some, most, or even all of their research. Since NOAO now includes only 20% of the telescopes with apertures of 2 meters or greater, the "annual" category is extremely competitive scientifically, and NOAO has played a fundamental role in enabling these scientists and their graduate students to conduct their research.

Figure 4 shows more detailed breakdowns of the NOAO budget in 1993, the most recent year for which such data are available. Figure 4a represents funding explicitly designated for support of Kitt Peak National Observatory (KPNO); Cerro Tololo Inter-American Observatory (CTIO); the U.S. Gemini Project Office (USGPO); general administrative, scientific, and technical support at the NOAO Tucson headquarters ("central") and the Association of Universities for Research in Astronomy, Inc. (AURA), management fee (vertically shaded); and support of solar astronomy (horizontally shaded) through the National Solar Observatory at Sacramento Peak (NSO/SP) and Tucson (NSO/T) and the Global Oscillation Network Group (GONG). Figure 4b shows the distribution that results when the Tucson central services and AURA management are prorated among the various functions they support, according to estimates provided by NOAO. In Figure 4b, the support of the image reduction and analysis facility (IRAF) project, the USGPO, and the WIYN telescope are shown separately. The chart shows that of the $27.1 M NOAO budget for 1993, $18.6 M was devoted to support of nighttime OIR astronomy and $8.5 M was devoted to solar astronomy.

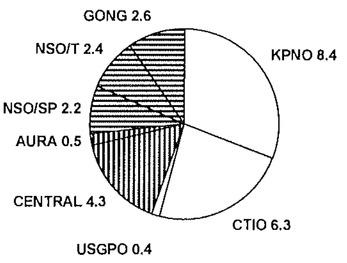

Figure 4a. The 1993 NOAO funding distribution (in $M; total is $27.1M).

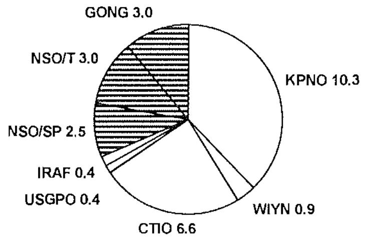

Figure 4b. The 1993 NOAO budget distribution with the Tucson central services and AURA management pro-rated among the various functions they support, based on estimates provided by NOAO (in $M; total is $27.1M).

Currently, NOAO has a net staff of 455 full-time equivalents (FTEs), of which 224 are located in the downtown Tucson headquarters, 48 are located at Kitt Peak, 41 at Sacramento Peak, and 142 at Cerro Tololo. Figure 5 shows the organizational distribution of the NOAO staff. Figure 6 shows the distribution of the CTIO staff according to function, and Figure 7 shows the same distribution of the KPNO and NOAO Tucson staff, excluding NSO and GONG. The net NOAO staffing devoted to nighttime OIR astronomy has decreased by about 6% from 1989 to 1994.

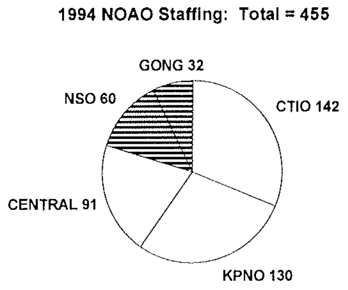

Figure 5. Distribution of NOAO staff by organization.

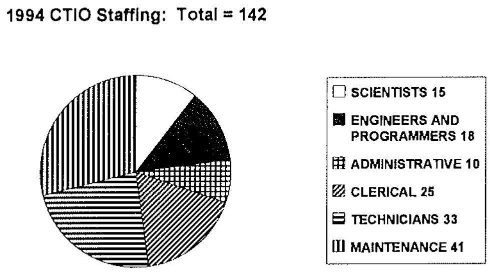

Figure 6. Distribution of CTIO staff according to function.

To understand the diversity of OIR facilities in the United States, it is important to consider the historical context in which the national observatories were established. In the early 1950s, the California astronomers had a monopoly on facilities at excellent sites, with the telescopes on Mt. Wilson, Mt. Palomar, and Mt. Hamilton. To enable scientists from other institutions to carry out front-line research in OIR astronomy, KPNO was founded in 1957 by a consortium of universities that established AURA to manage the operations for the NSF. CTIO was founded by NSF and AURA in 1964 to provide access to Southern Hemisphere skies. Since that time, most of the original signatories have built their own Northern Hemisphere telescopes and so are much less dependent on KPNO. In the meantime, departments of astronomy have grown in many universities that were not original signatories to the AURA agreement and that today do not have access to independent observatories. Approximately 50% of active OIR astronomers in the United States have access to independent observatories, while the remaining 50% must rely on NOAO for access to telescopes.

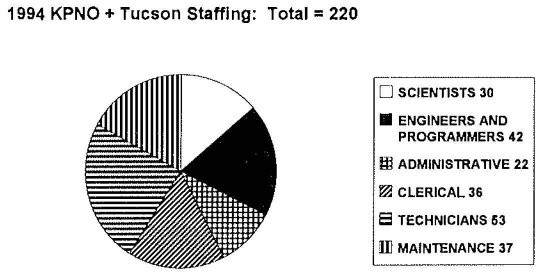

Figure 7. Distribution of KPNO plus NOAO Tucson staff according to function (excluding NSO and GONG).

Antarctic Programs

The NSF also supports OIR astronomy research at the South Pole through a grant of $21 M for five years from the Division of Polar Programs to the Center for Astrophysical Research in Antarctica (CARA), a consortium involving the Center for Astrophysics, Boston University, Carnegie Mellon University, the University of Chicago, and the University of Colorado. This program supports SPIREX, a 60-centimeter infrared-optimized telescope; ASTRO, a 1.7-meter submillimeter telescope; and COBRA, a 2-meter telescope to measure the anisotropy of the cosmic microwave background radiation.

NASA

The National Aeronautics and Space Administration Solar System Exploration Division supports the 3-meter Infrared Telescope Facility (IRTF) on Mauna Kea and has made a commitment to support part of the construction of the infrared-optimized Keck 2 telescope and future operations of the Keck telescopes in return for 1/6 time on the two Keck telescopes. The NASA telescope time will be available for national access through peer-reviewed competition. Observations related to solar system studies and origins of planetary systems will have priority

The Independent Observatories

Table 2 lists all current and planned telescopes with aperture greater than 2.0 meters that will be available to U.S. astronomers, including both the "national" telescopes operated by NOAO and NASA and those telescopes operated by independent observatories (including the Smithsonian Astrophysical Observatory). It shows that the telescopes at the independent observatories currently comprise roughly 81% of the total collecting area (and 76% of the net diameter) of such telescopes and that this situation will prevail for the foreseeable future. Even more remarkable is the fact that the net area of all major U.S. telescopes will increase by a factor of 2.45 within a decade. The net capital investment (not including operating expenses) of private and state funds in telescopes that will be built by the independent observatories between 1985 and 2000 already exceeds $250 M and will certainly exceed $300 M before the end of the century.

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*Abt, H. 1990. *Publ. Astron. Soc. Pacific* **92**, 249 (1980); **97**, 1050 (1985); **105**, 794 (1993).

Table 2. Current and Planned U.S. Telescopes with Aperture Greater Than 2.0 Meters

Public Observatories			Independent Observatories		
Telescope	Aperture (m)	Area (m^2)	Telescope	Aperture (m)	Area (m^2)
CURRENT					
KPNO	4.0	12.6	Keck 1	10	78.5
CTIO	4.0	12.6	Palomar	5	19.6
0.4 × WIYN	3.5	9.6	MMT	4.5	15.9
KPNO	2.1	3.5	ARC	3.5	9.6
0.9 × IRTF	3.0	7.1	0.6 × WIYN	3.5	9.6
			Lick	3	7.1
			Texas	2.7	5.7
			Dupont	2.5	4.9
			MDM	2.5	4.9
			WIRO	2.4	4.5
			Steward	2.3	4.2
			Hawaii	2.2	3.8
			Texas	2.1	3.5
SUBTOTAL*	14.2	38.9		44.8	167.8
	24%	19%		76%	81%
PLANNED					
0.45 × Gemini N	0.45 × 8	50.3	0.9 × Keck 2	10	78.5
0.45 × Gemini S	0.45 × 8	50.3	0.5 × LBT	2 × 8.5	113.4
1/3 × Keck 1	1/3 × 10	78.5	0.5 × HET	~ 8	35.2
			Magellan I	6.5	33.2
			Magellan II	6.5	33.2
			MMT upgrade	6.5	33.2
			SDSS	2.5	4.9
SUBTOTAL*	10.5	71.4		42.8	248.7
	20%	22%		80%	78%
TOTAL*	24.7	110.3		83.0	400.7
	23%	22%		77%	78%

*The actual telescope apertures or areas are listed, but these values are multiplied by the fractions of time allocated to U.S. astronomers to calculate the subtotals and totals. The sums in the independent observatories column do not include the University of Hawaii shares of international telescopes on Mauna Kea, such as Gemini North, the CFHT, the United Kingdom Infrared Telescope, and the Subaru Telescope. The MMT upgrade replaces the MMT, whose contribution has been subtracted from the total.

Key to Table 2:

ARC: Located at Apache Point Observatory, New Mexico, and operated by the Astrophysics Research Corporation, a consortium of the University of Chicago, New Mexico State University, Princeton University, the University of Washington, and Washington State University.

CFHT: Canada-France-Hawaii Telescope.

Dupont: Located at Las Campanas Observatory, Chile, and operated by the Carnegie Observatories.

Gemini N: (See Plate 1.) Located on Mauna Kea and operated by the IGP. Time allocation: U.S. national access—45%; international partners—45%; University of Hawaii—10%.

Gemini S: Located on Cerro Pachon, Chile, and operated by the IGP.

Hawaii: The University of Hawaii Telescope.

HET: Hobby-Eberly Telescope, located at MacDonald Observatory, Texas; a collaboration between the University of Texas, Pennsylvania State University, Stanford University, the University of Munich, and the University of Göttingen.

IRTF: The Infrared Telescope Facility located on Mauna Kea and operated by NASA Planetary Sciences Division.

Keck 1: (See Plate 2.) Located on Mauna Kea and operated by CARA, a consortium of the California Institute of Technology and the University of California system.

Keck 2: Twin of the Keck 1 telescope under construction on Mauna Kea. Funded partially by NASA Planetary Sciences Division, which will provide national access to 1/6 of the telescope time of both Keck 1 and Keck 2. The remaining time will be under the control of the California Institute of Technology and the University of California system.

LBT: Large Binocular Telescope, located on Mt. Graham, Arizona; a collaboration between the Steward Observatory, University of Arizona; Arcetri Observatory, Florence, Italy; and Research Corporation, a U.S. foundation for the advancement of science.

Lick: Shane Telescope, located on Mt. Hamilton, California, and operated by the Lick Observatory, University of California.

Magellan I: Located at Las Campanas Observatory, Chile; a collaboration between the Carnegie Observatories and the University of Arizona.

Magellan II: Twin to Magellan I telescope.

MDM: Located on Kitt Peak and operated by the University of Michigan, Dartmouth University, and the Massachusetts Institute of Technology.

MMT: Multiple Mirror Telescope, located on Mt. Hopkins, Arizona, and operated jointly by the University of Arizona and the Smithsonian Astrophysical Observatory. To be upgraded to a single-mirror telescope and renamed the Monolithic Mirror Telescope.

Palomar: Located on Mt. Palomar, California, and operated by the California Institute of Technology in partnership with the Carnegie Observatories and Cornell University.

SDSS: Sloan Digital Sky Survey, located at Apache Point Observatory, New Mexico, and operated by a consortium including the University of Chicago, Fermilab, the Institute for Advanced Study, Johns Hopkins University, Princeton University, the University of Washington, the U.S. Naval Observatory, and a number of astronomical institutions in Japan.

Steward: Located on Kitt Peak and operated by the Steward Observatory, University of Arizona.

Texas: Operated by MacDonald Observatory, University of Texas.

WIRO: Wyoming Infrared Observatory, operated by the University of Wyoming.

WIYN: Located on Kitt Peak and operated jointly by the University of Wisconsin, Indiana University, Yale University, and NOAO. Forty percent of the observing time is available for national access via NOAO, and 60% remains in the control of the participating universities.

III. OPPORTUNITIES IN OIR ASTRONOMY

The Allure of Astronomy

Astronomy occupies a special place in the research portfolio of this country. Understanding the stars and the cosmos is one of the oldest and noblest intellectual goals of humanity. The compelling justification for astronomy research is immediately clear and its results, in particular the beautiful images obtained in the optical and infrared, excite the imagination of the public at large, as witnessed by the wide coverage of astronomy research in the media. Starting in the first years of primary school, astronomy offers numerous opportunities to improve the scientific literacy of our population, and many astronomers are becoming actively involved in K-12 education. From planetarium shows to the use of computers in the classroom, exciting approaches are being tried. Moreover, for many undergraduates of our universities, the only contact with modern science is established through an introductory course in astronomy. The recent increase in the number of astronomers may be less a consequence of federal funding than the response by universities to student demand for these highly popular courses.

Although astronomy represents the essence of basic research, it is also intimately engaged in the applied field of instrumentation in its increasingly closer interaction with industry. Astronomy's research activities depend on the development of sophisticated sensors, and the availability of low-noise and large-format CCDs and infrared arrays has produced in the last decade a revolution in our observing power. Adaptive optics and interferometric methods promise to have the same effect in the coming years. Inversely, the demanding needs of astronomy and the efforts of brilliant instrumentalists contribute to advancing the state of the art in technologies applicable to many other scientific fields and to the commercial, medical, and defense sectors. The current trend of instrument development in a university setting offers the additional advantage of involving undergraduate and graduate students, and therefore training scientists and engineers who become familiar with essential enabling technologies. Similar comments could be made about the high-performance computing increasingly necessary for data reduction, simulation of complex phenomena like galaxy formation and supernovae explosions, and archiving.

The Promise of New Technologies

Before the advent of radio astronomy in the 1940s, most of the great discoveries in astronomy were made with large reflecting telescopes in which the light was detected by photographic film. A new technological revolution in OIR astronomy began in the 1970s, when astronomers started to replace photographic film with electronic detectors such as CCDs, effectively increasing the light-gathering power of the telescopes by factors of 10 to 30. This revolution continues today, with major advances arising from:

- *Active control of the shapes of telescope mirrors.* With this technology, it is possible to build large telescopes with lightweight thin or segmented primary mirrors of short focal length. Greatly reduced costs result from much lighter support structures and smaller domes. The Keck 1 (Plate 2) and WIYN telescopes have demonstrated that this technology can provide image quality better than that provided by telescopes with massive solid mirrors.

- *New designs for telescope mounts and instrument platforms.* New-technology telescopes permit the simultaneous installation of several major instruments. They can be used at much higher efficiency than older telescopes because astronomers can switch from one instrument to another in minutes instead of hours or days, carrying out complex observational programs and optimizing the instrument choice to changing observing conditions.

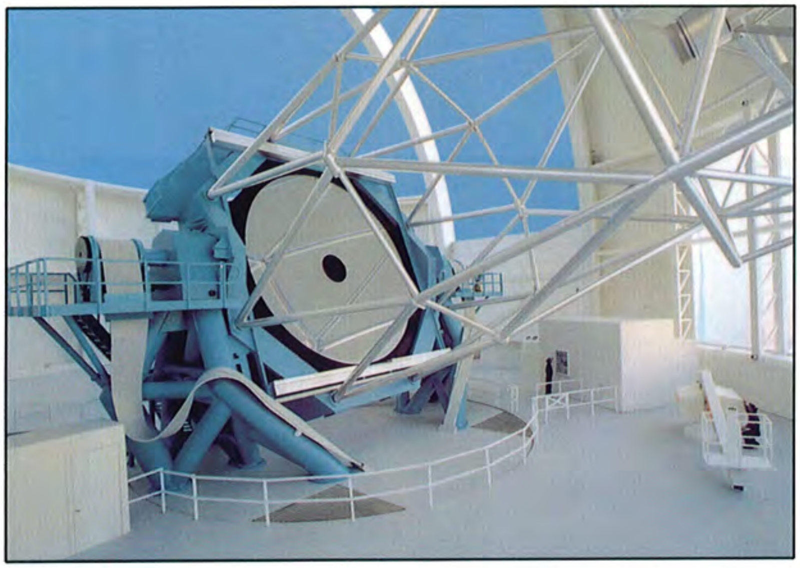

Plate 1. Scale model of the Gemini North telescope. The 8-meter-diameter primary mirror is relatively thin and flexible. Deformations are removed by some 120 computer-controlled actuators on the mirror mount to give the sharpest possible image. The secondary mirror is supported by a truss structure designed to minimize the infrared radiation that enters the telescope. The open design of the dome minimizes image degradation due to turbulence in the local airflow. (Courtesy of National Optical Astronomy Observatories.)

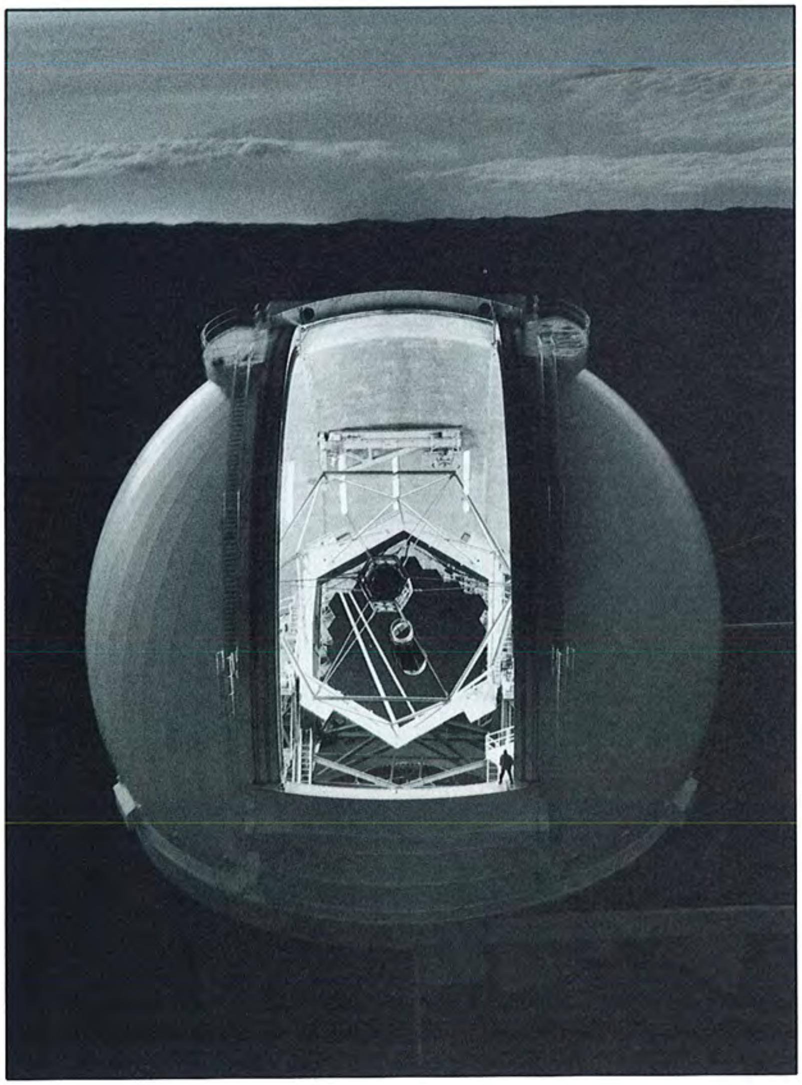

Plate 2. The world's largest telescope: the 10-meter-diameter mirror of the W. M. Keck Telescope, atop Hawaii's dormant Mauna Kea volcano, was completed April 14, 1992. The positions of its 36 hexagonal glass segments are aligned to a small fraction of the wavelength of light by computer-controlled actuators. A twin telescope, Keck 2, to be located nearby, is currently under construction and will be completed in 1996. The Keck telescopes are the results of a scientific partnership between the California Institute of Technology and the University of California. (Courtesy of Roger Ressmeyer, Starlight Photo Agency.)

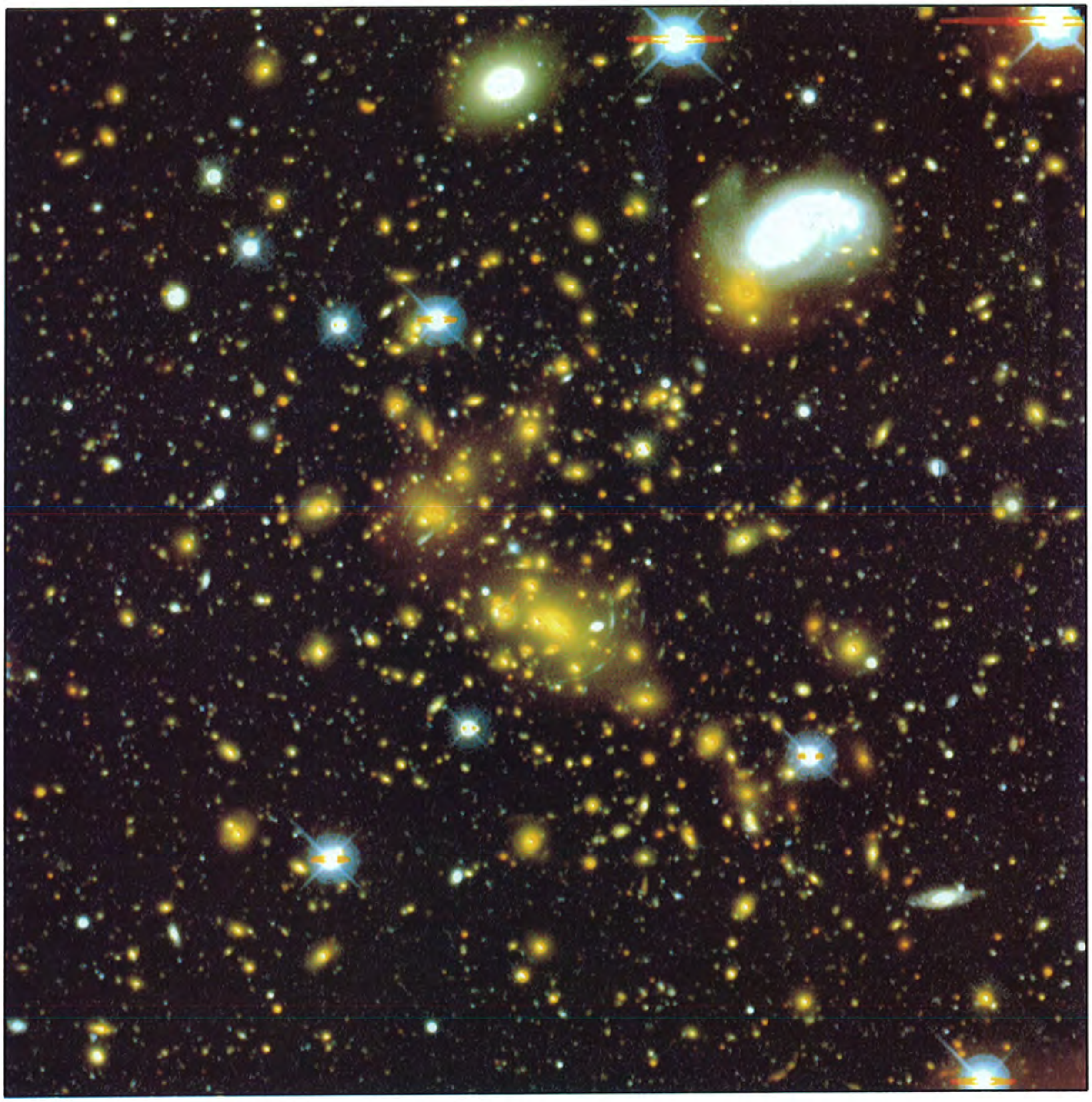

Plate 3. The deep extragalactic sky. Large ground-based telescopes equipped with state-of-the-art wide-field CCD imagers are uniquely capable of probing the distant universe. For example, more than 10,000 galaxies can be detected in this image, taken with such a camera on the 4-meter Mayall telescope on Kitt Peak National Observatory. Fewer than 100 of them would be detectable in a similar image taken with photographic film, the best available technology for wide-field imaging in 1980. The faint blue arcs circling a massive cluster of reddish-yellow galaxies are actually much more distant blue galaxies elongated by gravitational lensing as their light passes through this cluster (Abell 2218) 2 billion light-years distant. These distorted background images can provide a map of the mass of the foreground cluster, most of which is otherwise invisible dark matter. (Courtesy of Gary Bernstein, University of Michigan, and J. Anthony Tyson, AT&T Bell Laboratories.)

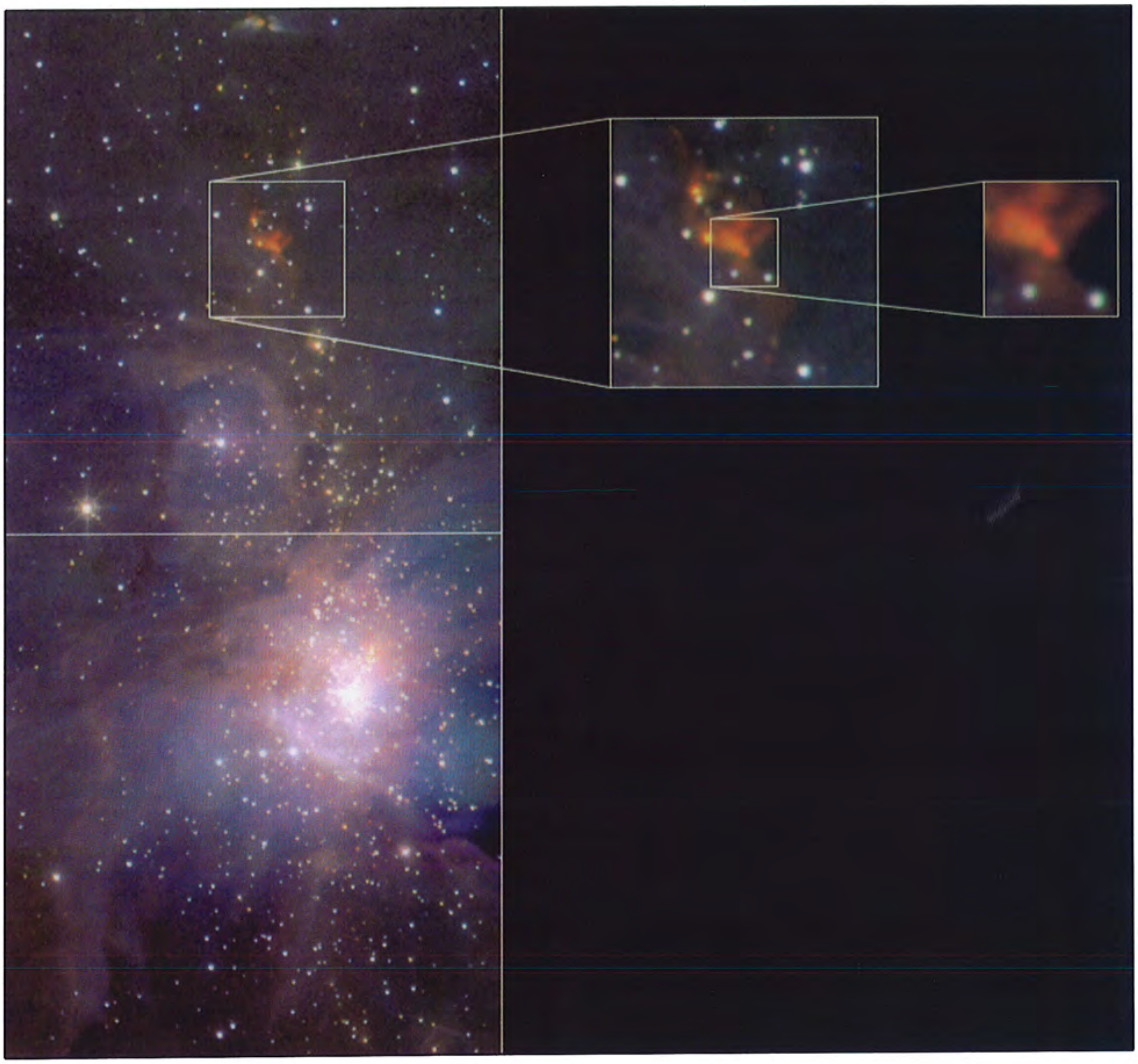

Plate 4. Infrared array images of the Orion Nebula, a nearby region of active star formation. Most of the stars seen in this image are invisible at optical wavelengths as a result of obscuration by interstellar dust. The reddest objects are highly obscured newly forming stars. The insets illustrate the dramatic advance in infrared array detector technology. The inset at the upper right represents an array of 58 × 62 pixels, the best available in 1990. The middle inset represents an array of 256 × 256 pixels, the present technology. The larger square panels on the left are montages, each constructed from 16 such images. By 1996, such images will be obtained in a single observation with arrays of 1024 × 1024 pixels currently under development. To produce a comparable image in 1990 would have required roughly 300 times as much telescope time. (Courtesy of National Optical Astronomy Observatories.)

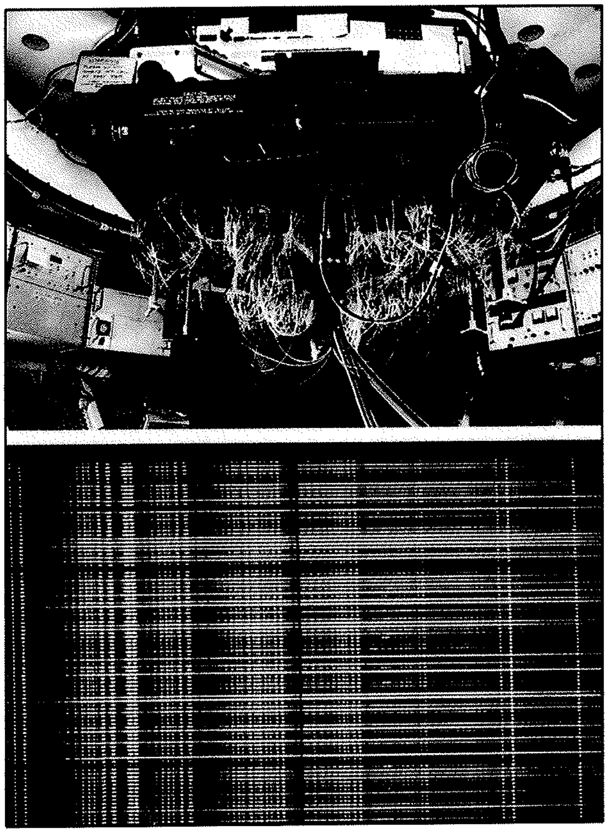

Plate 5. (Top) The Hydra multifiber spectrograph mounted on the 4-meter Mayall telescope at Kitt Peak National Observatory. Each of 97 optical fibers can be placed by computer control to capture and analyze the light from a different part of the telescope image. (Bottom) The spectra of 97 galaxies obtained simultaneously by the Hydra spectrograph. Each horizontal line is the spectrum of light from a different galaxy. The bracket at the bottom indicates the wavelength range where pairs of emission lines from hydrogen and sulfur atoms in galaxies are evident in many spectra. The lines can be recognized easily because they do not line up vertically at constant wavelength, owing to the motions of the galaxies. (Most of the emission lines in the spectra actually come from the Earth's airglow.) By analyzing these wavelength shifts, astronomers can measure the mass of dark matter between the galaxies. (Courtesy of National Optical Astronomy Observatories.)

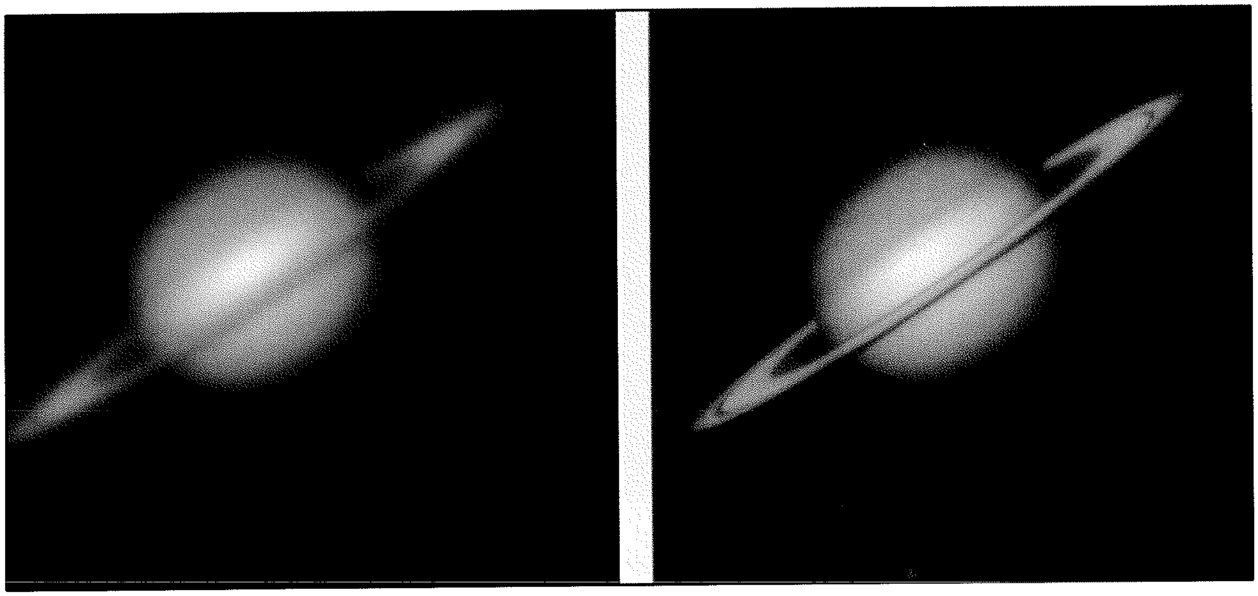

Plate 6. Saturn with and without adaptive optics. (Left panel) The image is blurred by atmospheric turbulence to a resolution of approximately 1.5 arc seconds. (Right panel) The image resolution has improved to approximately 0.2 arc seconds with an adaptive optics system. A laser system measures the atmospheric image distortion and 241 actuators deform a mirror at a rate of 100 times per second to remove this distortion. Details, such as the gaps in the rings, the band structure of Saturn's atmosphere, and the satellite Titan, are now clearly visible. (Courtesy of Robert Q. Fugate, Starfire Optical Range, U.S. Air Force Phillips Laboratory.)

- *Improved design and thermal control of telescope domes.* This technology (see Plate 1) can result in improvements of image quality and spectrometer throughput by factors of two or more.

- *Large-format blue-sensitive optical CCD arrays.* Such arrays (Plate 3) can make full use of the focal plane of moderate telescopes designed for wide-field imaging and spectrometry, such as the 0.6-meter Burrell Schmidt telescope and the 2.5-meter Sloan Digital Sky Survey telescope at Apache Point Observatory. Current plans for instruments on the Keck telescopes include arrays of 8,000 × 8,000 pixels.

- *Large-format infrared arrays.* This development is the greatest recent advance in instrument technology for OIR astronomy. High-quantum-efficiency, very-low-noise, low-dark-current arrays of up to 1024 × 1024 pixels have increased the ability of telescopes to obtain infrared images and spectra by factors of thousands compared to what was possible five years ago (Plate 4).

- *Multiobject spectrometry.* New spectrometers (Plate 5) equipped with multiple fiber-optic feeds or multiple slits can now take spectra of hundreds of objects at once rather than one at a time.

- *Computers and information technology.* Advances in these areas enable astronomers to analyze efficiently and develop meaningful models for the vast flood of data produced by the new instruments on OIR telescopes. They also permit greater versatility and accuracy in telescope control and the ability to assess and analyze data in real time. Thanks to high-speed telecommunications networks, it is now becoming possible for astronomers to operate telescopes located thousands of miles away with computer terminals in their home offices.

- *Adaptive optics.* Technology to correct for rapidly changing image distortion due to atmospheric turbulence, pioneered by the Department of Defense, is now becoming available to astronomers. A factor-of-two reduction in the full width at half maximum (FWHM) of the resolution of the image implies a factor-of-four increase in peak flux and a factor-of-eight improvement in accuracy of moment analysis, image distortion analysis, and morphological classification. Already, the Canada-France-Hawaii Telescope (CFHT) has demonstrated the ability of an adaptive tip-tilt system to reduce the seeing FWHM from 0.8" to 0.4". More sophisticated technologies to correct wavefront distortion more completely are currently under development (Plate 6). They have the potential of providing image quality that can now be obtained only by far more costly telescopes in space.

- *Interferometry.* The technology to combine in phase the light from separated telescopes, a standard technique for radio astronomy, opens the possibility of observing sources with angular resolution hundreds or thousands of times sharper than currently feasible from telescopes on the ground or in space. As discussed in the AASC report, such technology would enable astronomers to address exciting problems currently beyond reach. Great challenges remain to bring the technology to fruition.

Scientific Challenges

The AASC report identified the outstanding scientific opportunities in astronomy and astrophysics for the 1990s and laid out a prioritized strategy for realizing those opportunities. The AASC strategy for OIR astronomy is part of a larger strategy for research in astronomy and astrophysics that includes facilities on the ground and in space. The current revolution in our understanding of the cosmos comes largely from our new-found ability to observe the sky at every wavelength of the electromagnetic spectrum, ranging from radio to gamma rays. In this strategy, OIR astronomy plays a central role. Almost every new astronomical source, whether discovered by radio telescopes on the ground or by infrared, ultraviolet, X-ray, or gamma-ray telescopes in space, must be observed by ground-based OIR telescopes to understand its physical nature and significance.

Conversely, observations with ground-based OIR telescopes are essential for the efficient use of far more costly telescopes in space. For example, the Hubble Space Telescope (HST) has a very narrow field of view and can observe only a tiny fraction of the sky. We can realize the full benefits of the HST's superior image quality and unique ultraviolet spectroscopic capability only if we identify its targets on the basis of extensive studies with ground-based OIR telescopes. Moreover, the HST will image distant sources so faint that their spectra can be measured only by ground-based OIR telescopes of far greater aperture. The same considerations apply to other NASA programs under development, such as the NICMOS infrared instrument on HST, the Space Infrared Telescope Facility (SIRTF) and the Stratospheric Observatory for Infrared Astronomy (SOFIA) infrared telescopes, and the Advanced X-ray Astrophysics Facility (AXAF) X-ray telescope. Even ignoring the scientific discoveries enabled by OIR telescopes alone, NSF's $40 M annual expenditure to support ground-based OIR astronomy can be justified easily on the basis of the enhanced scientific yield from NASA's $800 M annual funding of space astrophysics.

The AASC report pointed out that major opportunities to address fundamental cosmic questions will be enabled by new technologies and instrumentation for ground-based OIR telescopes. For example:

- *How do stars form?* Telescopes equipped with modern infrared instruments will be able to observe newly forming stars that are enshrouded in dust clouds from which optical light cannot emerge. The images will reveal the morphology of the disks and jets around these stars, and the spectra will tell us about the gas temperatures, velocities, and magnetism that control the star formation dynamics.

- *What is the origin of the heavy elements in the universe?* Astronomers believe that the heavy elements are formed as a result of nuclear reactions in stars, particularly in their final convulsions as novae and supernovae. Surveys with 2- to 4-meter telescopes will find many more of these events, and large telescopes will obtain detailed spectra, particularly at infrared wavelengths where newly formed elements are most apparent, to confirm and enrich this theory. With powerful new spectrometers, astronomers will be able to understand better how the products of supernova nucleosynthesis are dispersed and built up in stars, galaxies, and interstellar and intergalactic gas.

- *How many stars have planetary systems?* With infrared telescopes, astronomers will be able to detect and image disks of dust particles around stars from which planetary systems are believed to form.

- *How do galaxies form and evolve?* With large optical and infrared telescopes, astronomers will be able to find newly forming galaxies at high redshifts and learn about their dominant physical processes.

- *What powers the central engines of active galaxies and quasars?* Are they supermassive black holes? Do many other galaxies, including the Milky Way, also contain quiescent black holes? If so, what are the environmental conditions that determine the rich variety of phenomena associated with quasars and galactic nuclei? To answer these questions, astronomers need to observe many galactic nuclei with OIR telescopes having high angular resolution, broad spectral range, and polarimetric capability. The coordination of such observations with observations with radio, ultraviolet, X-ray, and gamma-ray telescopes is also necessary.

- *How did the matter in the universe coalesce into clusters and superclusters of galaxies, separated by huge voids?* With new-technology 2- to 8-meter wide-field telescopes instrumented to measure spectra of hundreds of galaxies at a time, astronomers will be able to map the distribution and velocities of many thousands of galaxies at moderate and high redshifts, and to understand the forces and motions caused by the unseen "dark matter" that appears to dominate the mass of the universe. With infrared telescopes, they will be able to search deeply for faint red stars that may contribute to the dark matter in the halos of galaxies.

The AASC report recognized that the most dramatic advances in these and other areas would probably come from observations in the infrared band, where many of these phenomena are most easily observed. Great advances in our ability to obtain infrared images and spectra are now being achieved with new large-scale array detectors with high quantum efficiency and very low noise and dark current. Moreover, the opportunity to obtain much sharper images from ground-based telescopes will be realized first at infrared bands, for which the effects of atmospheric distortion are most easily compensated. For these reasons, as well as the scientific promise of proposed NASA observatories such as SOFIA and SIRTF, the AASC report called the 1990s "the decade of the infrared."

Dramatic confirmation of the prescience of that remark comes from the impact of comet Shoemaker-Levy 9 with Jupiter. The effects are most clearly evident in infrared images taken with telescopes equipped with adaptive optics correctors and wide-format infrared array detectors that were not available five years ago. Even as this report is written, these images are appearing on the front pages of the world's newspapers, magazine covers, and television news broadcasts. This remarkable event, the likes of which may not recur for millennia, will tell us much about the nature of comets, the atmosphere of Jupiter, and the mechanisms for mass extinctions that occur on Earth on time scales of tens of millions of years.

The Diversity of OIR Astronomy

The sky contains literally billions of sources visible to OIR telescopes, representing an amazing variety of phenomena. A partial list includes:

- Planets, moons, comets, and asteroids;
- Violent magnetic storms on nearby stars;
- Giant stars that are blowing their outer layers into interstellar space;
- Violent stellar explosions in novae and supernovae;
- Interacting binaries containing the collapsed remnants of dead stars;
- Vast clouds of magnetized interstellar gas violently disturbed by stellar outflows and explosions;
- Newly forming stars surrounded by whirling disks and shooting out jets of gas;
- Galaxies with a vast variety of sizes, shapes, content, and dynamical behavior, which are observed to evolve as we look further back in distance and time;
- Active galaxies and quasars containing compact sources of enormous power at their centers;
- Clouds of diffuse gas between the galaxies observable by their absorption of ultraviolet radiation from distant quasars; and
- An expanding universe in which the galaxies are distributed on filaments separating great voids and move under the influence of a far greater mass of invisible matter.

Even using all the telescopes available, only a tiny fraction of these sources can be observed in a human lifetime. A strategy to optimize progress in understanding such a sky will not be highly focused—it will require great diversity of facilities, observing strategies, and ideas.

The commissioning of the two powerful Gemini telescopes in 2000 and 2003 will open new opportunities for research by the U.S. astronomical community. The 8-meter Gemini North telescope on Mauna Kea was the AASC report's highest-priority recommendation for a ground-based facility. It will be optimized for diffraction-limited operation at infrared wavelengths and will be a unique facility using revolutionary infrared array detectors to make the high-spatial- and high-time-resolution observations needed to study phenomena ranging from protoplanetary disks around young nearby stars to the most distant galaxies in the early universe. The 8-meter Gemini South telescope, located in Chile (see back cover), will provide U.S. astronomers with a vital window to the Magellanic clouds, the center of the Milky Way, and other southern sky objects.

The estimated annual cost for the IGP to operate the two Gemini telescopes will be about $11 M, of which the United States is obliged to provide half. In addition, NOAO estimates an annual cost of $2.5 M to support access by the U.S. community to the Gemini telescopes, including partial support for continued instrument development, observer support, and analysis and archiving of data. The net cost, $8 M, is well within the normal guidelines for the operation of any major astronomical facility, which is about 10% per year of the construction costs.

Modern OIR astronomy involves a mix of telescope sizes and types. The largest and most expensive telescopes, such as the 8-meter Gemini telescopes (see Plate 1) and the 10-meter Keck telescopes (see Plate 2), will have unique power to record images and spectra of the faintest and most distant sources in the sky. But it would be extremely wasteful to use these great telescopes to observe systems that can be observed equally well, and often far more efficiently, by smaller telescopes. For example, these great telescopes have relatively narrow fields of view, whereas modern 2-to 4-meter-class telescopes can observe a far greater number of sources at once because they have larger fields of view. Thus, a strategy for efficient use of the large telescopes requires smaller telescopes to select the most promising targets from the myriad of sources. Moreover, there are many projects of great scientific merit, such as redshift surveys and mapping of extended sources, that can be done more efficiently with smaller telescopes.

In addition to large and moderate general-purpose telescopes, an efficient infrastructure for OIR astronomy will include telescopes designed for special purposes. Some important programs can be accomplished at great savings in telescope construction and operation by sacrificing versatility. For example, the Hobby-Eberly Telescope (HET; see Table 2) has a 10-meter fixed spherical primary mirror and a movable secondary mirror—the optical equivalent of the Arecibo radio telescope. By sacrificing pointing and steering capability, the HET can measure spectra of faint objects at a small fraction of the cost of doing so with a general-purpose telescope of comparable effective aperture (6 to 8 meters). Other very important projects, such as the Two Micron All Sky Survey (2MASS) of millions of infrared sources and the Sloan Digital Sky Survey (SDSS) to measure the colors and spectra of millions of galaxies and quasars, can be carried out only with dedicated special-purpose telescopes.

An efficient strategy for OIR astronomy will also accommodate a diversity of observing modes. Programs to develop new instrument technology will require substantial amounts of dedicated telescope time. Some observations, which push the performance limits of telescopes and instruments, can be carried out successfully only by astronomers intimately familiar with the facilities. Uniform surveys of large numbers of sources may require tens or hundreds of nights of telescope time but can be carried out according to an established routine. Some such programs may now be accomplished most efficiently by remote observing. At the other extreme, a new discovery at radio or X-ray wavelengths may require a snapshot taking only a few minutes of telescope time or, as is frequently the case, it may lead to an extensive campaign for coordinated ground- and space-based OIR observations. Much important science can be achieved most efficiently by creating a large uniform data set and analyzing the results later, as was the case with the Infrared Astronomy Satellite and will likely be so for the SDSS. These various observing modes will complement, but not replace, the traditional observing run of a few nights, which will still be needed for experienced astronomers to carry out many kinds of programs and to provide hands-on training of new astronomers.

Some observations might be done best if scheduled in a queue and executed by staff astronomers instead of the investigator, much as most observations with space observatories are carried out. Queue scheduling can be efficient because it permits (1) observations that require rare conditions such as exceptional seeing; (2) greater efficiency in executing short observations; (3) greater flexibility in ensuring that observations of highest scientific priority are executed; (4) ease of scheduling time-critical observations such as targets of opportunity and synoptic studies; and (5) optimal scheduling of observations to ensure observations at minimum air mass and correct lunar phase.

Most of the major OIR telescopes in the United States are located at independent observatories, owned and managed by state and private institutions (see Section II). This situation, in which the majority of the capital assets were provided by private and state sources, is a unique and enormous asset to U.S. physical science. Because these independent observatories operate more than two-thirds of the major U.S. telescopes and are used primarily by about half of the OIR astronomers in the United States (Section II), they can support scientific programs of great merit that are beyond the resources of the NOAO. In particular, the independent observatories can devote greater fractions of their telescope time to testing of innovative instrumentation and to extensive observing projects requiring tens or hundreds of nights of telescope time. The independent observatories also make a major contribution to the research of astronomers not affiliated with their own institutions, through informal collaborations, guest observer programs, and the data that they disseminate to the community.

NOAO adds a vital dimension to OIR astronomy (and solar astronomy) in the United States. Since KPNO began operations in 1960, NOAO has provided world-class telescopes, particularly the 4-meter telescopes at KPNO and CTIO. The CTIO has been especially important to U.S. astronomers because its facilities have provided vital access to the southern sky (the only other major U.S.-owned Southern Hemisphere telescope is the 2.5-meter Dupont telescope of the Las Campanas Observatory). NOAO enables many astronomers at universities without major telescopes to carry out frontier research on the basis of open peer-reviewed competition. NOAO also provides crucial observing options not otherwise available to astronomers at independent observatories. Likewise, NOAO provides vital access to OIR telescopes for radio and space astronomers.

The NOAO includes the National Solar Observatories (NSO), which provide the U.S. solar physics community with access to observing capabilities not available elsewhere in the United States. These include the infrared capabilities of NSO facilities on Kitt Peak and the high-angular-resolution facilities in the optical at Sacramento Peak.

Recently, NOAO has entered into a number of successful partnerships with university instrument groups and independent observatories, such as the deployment at CTIO of the OSIRIS infrared spectrometer that was developed by Ohio State University, and the construction and joint operation at KPNO of the WIYN telescope, a partnership of the University of Wisconsin, Indiana University, Yale University, and NOAO. NOAO has exerted leadership in some areas of instrumentation development. Outstanding recent examples are the Hydra multifiber spectrograph (see Plate 5) and the deployment of large-format optical and infrared detector arrays. NOAO has acted as a national resource for instrumentalists by providing advice and technical information freely. NOAO has also developed and supported standards for data archiving and analysis, including the IRAF data-reduction software that is used by astronomers worldwide.

OIR astronomy in the United States gains strength not only from the infrastructure of the independent observatories and the NOAO, but also from a growing variety of international collaborations. The State of Hawaii has the good luck to have, on Mauna Kea, the best site in the world for many kinds of OIR astronomy (see front cover); as a result, the University of Hawaii is a partner in the operations of several international telescopes, notably the 3.6-meter CFHT, the 3.8-meter United Kingdom Infrared Telescope, and the 8-meter Japanese Subaru Telescope, currently under construction. International cooperation will become a much greater part of the U.S. OIR astronomy infrastructure with the completion of the two 8-meter telescopes of the international Gemini project, a collaboration between the United States (50% share), the United Kingdom (25%), Canada (15%), Chile (5%), Brazil (2.5%), and Argentina (2.5%). In addition, a number of independent observatories have undertaken to build major OIR telescopes in partnership with other countries, notably the Large Binocular Telescope (LBT), the HET, and the SDSS (see "The Independent Observatories" in Section II).

Principles for Maximizing Scientific Yield

Given the diversity of scientific challenges for OIR astronomy, it is no easy task to suggest mechanisms to optimize the productivity of the complex infrastructure that is required to meet them. Indeed, this panel cannot dictate how this infrastructure will develop or foresee the scientific and technical problems and opportunities that will arise. The best that it can do is to identify some general principles to increase the scientific yield of the enterprise, and suggest mechanisms for making ongoing decisions that are likely to lead to a more optimum infrastructure. The principles are as follows:

- It is wasteful to maintain a full complement of instruments on every telescope. Losses accrue from leaving valuable instruments on the shelf most of the time and from the necessity to change instruments. Significant savings can be realized by supporting fewer instruments on each telescope.

- If telescopes become more specialized, the diversity of observing options required for OIR astronomy can be maintained by arrangements facilitating access by astronomers to a variety of specialized telescopes at independent and national observatories. Various successful examples already exist of such arrangements, which are often informal. They include bartering of telescope time, exchange of telescope time for instruments, and service observing. Rapidly developing technology for remote observing will make it easier to provide such access.

- A broad distribution function of the length of observing runs will probably result in the greatest scientific yield. Long-term projects, by experienced observers with one or two instruments, can be of great scientific merit and can be carried out at the lowest cost per night. Many significant observations, particularly those on the largest telescopes, will require less than a night and might be accomplished most efficiently by queue scheduling and remote or service observing.

- Cooperation at every level should be encouraged. Already evident are excellent examples of cooperation between NOAO and various universities in building and operating telescopes (e.g., the WIYN telescope), in the deployment of instruments (e.g., the Ohio State University OSIRIS infrared spectrometer and the Rutgers University Fabry-Perot camera at CTIO), in the development of optical and infrared detector arrays, and in software development for instrument and telescope control as well as data analysis. Ongoing efforts to establish and maintain standards for user-telescope-instrument interfaces will encourage and facilitate such cooperation.

- Excellent opportunities will likely arise for international cooperation beyond the various agreements already mentioned to build new telescopes. For example, the Anglo-Australian Telescope and the CTIO are already discussing arrangements to barter telescope time. In the future, the Keck, Gemini, and European Southern Observatories may find that barter arrangements may reduce the need to build similar instruments at each observatory.

- Mechanisms for such cooperation will be most effective if the terms can be arranged by the working scientists and can evolve with changing circumstances.

An effective way to implement increased collaboration and cooperation and exchange of ideas would arise from increased national access to private observatories. A mechanism for facilitating such access is described in this report. Increased cooperation would not only foster new science programs, but would also provide enhanced opportunities for graduate student training.

IV. NOAO IN THE GEMINI ERA

Introduction

NOAO's mission is to provide national access to the sky by means of excellent optical and infrared observational facilities on outstanding sites in both hemispheres. Use of the facilities is determined by open peer-reviewed competition among the best scientific ideas from the entire astronomical community. The multiwavelength community has been very well served by the competitive access to NOAO facilities, and that must continue.

(Here, and throughout this report, the panel refers to NOAO's priorities and strategy for ground-based nighttime OIR astronomy. It does not discuss priorities for solar astronomy.)

Approximately half of the nation's active research astronomers have access to major telescopes at independent observatories, and approximately half are affiliated with institutions that lack such facilities. Many of the former group count on NOAO to provide observing options not available at their own observatories. For these astronomers, CTIO is especially valuable. The latter group includes many astronomers actively engaged in research at other wavelength bands (e.g., radio astronomy, space astronomy).

Why has NOAO been a success? NOAO has (1) built major telescopes in good sites, (2) equipped them with good instruments, and (3) provided excellent service to astronomers. NOAO has built up teams of skilled engineers and scientists in the areas of optical and infrared detectors, controllers, cryogenics, optical fibers, and data analysis software. The smaller telescopes have been equipped, not with a fleet of instruments, but with dedicated-purpose ones, particularly CCD imagers. These well-instrumented small telescopes have played a major role in the successful science conducted by NOAO users.

Despite these successes, NOAO has lagged in the construction of new telescopes. The 3.5-meter WIYN telescope is the first new facility in two decades. In the past, NOAO has tried to satisfy the entire user community with an extremely broad mix of user services and instrumentation on most of its telescopes. This effort has sapped resources that would have been better focused on the construction of more technically advanced facilities.

NOAO provides a level of service not found at the independent observatories. A substantial share of NSF dollars going toward NOAO is appropriate since it is the *only* observatory open to all astronomers. The question of balance between NOAO and the independent observatories is one that has been raised repeatedly and that is addressed below.

In addition to providing national access to telescopes, NOAO aims to provide leadership in the development and operations of major new telescopes, in developing instrumentation and software, and in scientific research. NOAO has had substantial success in each of these areas. However, the fact remains that NOAO does not now and will not be able to maintain pre-eminence in all aspects of OIR astronomy. To achieve leadership in a constrained budget environment, NOAO will have to make hard choices in distributing its resources. The panel suggests the following guiding principle: **NOAO should concentrate its resources in those areas where it has the best chances to assert scientific leadership.** It follows that NOAO will not be able to maintain preeminence in all aspects of OIR astronomy, nor should it try to do so.

The Gemini Era

The twin 8-meter Gemini telescopes are being built to permit the national scientific community competitive access to two of the world's largest telescopes in two of the world's best sites. NOAO should play the key role in determining how the United States interacts with the Gemini telescopes, instrumentation choices, and scientific support of the two telescopes. **Gemini's science, instrumentation, and operations must be NOAO's highest priorities.**

It will be a challenge for NOAO management to realign its observatories to accommodate the needs of the astronomy community in the Gemini era. These needs include community access to state-of-the-art instruments and high-performance 2- to 4-meter OIR telescopes, as well as the Gemini telescopes. This renewal of the NOAO infrastructure is crucial to the future of U.S. astronomy and was the highest-priority recommendation of the AASC report. However, to ensure effective operations and access by a wide community to these new facilities during a period of flat or declining budgets, major components of the present NOAO would by necessity vanish. Renewal of facilities must lead to a decrease of long-term operating costs so that more science can be supported within a fixed budget.

This realignment will be painful, for a different mix of talents and projects will be needed. Planning such a realignment must include (1) rethinking the role of the national observatory and (2) restructuring to optimize the effectiveness of that new role. The panel believes that reorganization will be required and that elements of that reorganization might include the following:

- Enabling scientific programs that require both Gemini and smaller telescopes, and that need to be conducted in either or both hemispheres. All stages of a project would be included, from possible pre-Gemini surveys to follow-up post-Gemini observations. The instrumentation on the smaller CTIO and KPNO telescopes and the national time allocation committee procedures may require modifications.

- As NOAO focuses its attention on fewer tasks of high priority, it should evolve to a leaner and more focused organization, with fewer employees and a different mix than at present, a smaller staff in Tucson, and a smaller core of tenured scientists.

- More open two-way links with the community—from contributed software and hardware to active participation in all phases of the observatory—would help spread the burden and the responsibility.

- New instruments might often be developed through competitive selection among NOAO itself and other optimal groups or suppliers, who would then collaborate closely with NOAO. A mechanism to stimulate this process could be an annual U.S. workshop for astronomical instrumentation.

- A reduced selection of instruments, with more instruments permanently installed on each telescope, should require fewer personnel for operations and maintenance and result in lower costs.

- Some observational programs would be done more efficiently by remote, queue, and service observing than by hands-on operation of the telescopes.

- NOAO site directors should have as much authority as possible to operate their sites in a scientifically cost-effective manner.

- Older telescopes of all sizes that are expensive and/or inefficient to operate should be retired.

The Gemini Project

To save costs, the international Gemini project intends to utilize as much of the existing CTIO infrastructure as possible for Gemini South and as much of the Joint Astronomy Center (JAC) infrastructure in Hilo as possible for Gemini North. The current plan is for IGP to buy services, in cash, from CTIO and JAC. NOAO will have a minimal presence on Hawaii, at least in the initial stages of Gemini operations.

While IGP has the responsibility to build, operate, maintain, and upgrade the Gemini telescopes and their instruments, it will not support Gemini science. Each participating nation is expected to provide the scientific, technical, and administrative infrastructure required for its astronomers to use the telescopes. For the United States, that role must be filled by the U.S. Gemini Project Office (USGPO), a division of NOAO located at Tucson. For U.S. users of Gemini, the USGPO will manage the national time allocation committee and telescope scheduling and will provide scientific support to astronomers, including advice concerning instruments, data, observing requirements, and access to archives.

The panel anticipates that a substantial fraction of Gemini science may be carried out most efficiently through queue observing and, possibly, by remote observing. Therefore, the USGPO must be prepared to support hardware and software interfaces for U.S. users to wideband telecommunication links with Gemini North and South. As is the case with software development for data analysis (see the subsection "Instrumentation" below), the USGPO effort to develop remote observing capability should be part of a national effort, taking maximum advantage of expertise outside of NOAO.

According to current estimates, the IGP will require approximately $11 M per year to operate and manage its telescopes, including $3 M per year for instruments and major telescope upgrades. The NSF will therefore be obliged to pay approximately $5.5 M per year to the IGP for its 50% share. The panel examined these costs and has found them reasonable. They do not, however, include the costs for NOAO to support the U.S. interface to the IGP, as described above. NOAO estimates that the latter activities will cost approximately $2.5 M per year and plans to absorb those costs by reallocating resources within its present budget. The panel endorses this plan. However, as discussed below, NOAO cannot absorb the additional $5.5 M per year charge without making severe cutbacks in its present operations, including a major downsizing of the Tucson operations, and probably the closing or privatizing of most of its older telescopes on KPNO.

Other Telescopes

After the direct support of the Gemini telescopes, the second priority of NOAO must be the support of moderate (2- to 4-meter-class) telescopes with the best possible capabilities. NOAO needs a variety of such telescopes to (1) support the Gemini scientific programs and instrument development, (2) provide other unique national capabilities, and (3) support the scientific programs of the best researchers and students throughout the nation. Items (2) and (3) are chief among NOAO's current activities, and the need to support them will not diminish with the coming of Gemini.

The new-technology 3.5-meter WIYN telescope at KPNO is an excellent example of a modest-class telescope. WIYN has already achieved an image quality better than 0.5". It will complement Gemini North in the intermediate field of view, high-resolution imaging regime; it will provide wide-field multiobject spectroscopic capabilities; and it will provide access to the near ultraviolet (UV). The latter capability will be important because the majority of the faintest and most distant objects are in fact UV-bright.

The WIYN experience is a very promising model for NOAO. Not only does WIYN yield much better image quality than any other KPNO telescope, but it also requires roughly only half as many FTEs (7 versus 16) to maintain, compared to the KPNO and CTIO 4-meter telescopes. Replication of the WIYN telescope is estimated to cost approximately $12 M and would pay for itself, in terms of reduced maintenance cost relative to the current 4-meter telescopes on KPNO and CTIO, in less than 20 years.

At CTIO, the current 4-meter telescope can provide wide-field imaging and some spectroscopic capability, but a new-technology 4-meter-class telescope is very much needed. Given the outstanding conditions available at Cerro Pachon, where the median seeing is roughly 0.4", a telescope with superb imaging capabilities would be exceptionally productive scientifically. The current 4-meter telescopes, built over 20 years ago with old technology, likely cannot be upgraded to better than 0.5" optics. At CTIO, a new-technology telescope would complement or replace the existing 4-meter telescope, just as WIYN complements the KPNO 4-meter.

Cerro Tololo Inter-American Observatory

In the Gemini era, CTIO will have the responsibility for supporting operations at Gemini South, as well as the support of existing CTIO telescopes. CTIO, with or without Gemini, is the *only* access to the Southern Hemisphere skies for the vast majority of U.S. astronomers, and its smaller telescopes should be kept open until they can be replaced in a cost-effective manner. As discussed above, an enormous amount of valuable science can, and should, be done on moderate-size telescopes. Closing the smaller telescopes on CTIO, particularly the 1.5-meter and the Schmidt telescopes, should be done only as a last resort.

In order for CTIO staff to fulfill its obligations, the observatory should maintain an adequate engineering staff. Because of its remoteness, CTIO needs to be more self-sufficient than observatories in the Northern Hemisphere. The panel thus questions the wisdom of across-the-board cuts of the various components of NOAO, since these cuts have forced CTIO to gradually reduce its engineering staff to the point that it can no longer build facility instruments and has had to struggle to develop a CCD controller (ARCON). With subcritical staffing, it will be impossible for CTIO to maintain its current instruments, let alone even assist in the development of further instruments.

Kitt Peak National Observatory

As Gemini comes on line, NOAO will need to reduce the operations costs of KPNO. This cannot be accomplished simply by closing the smaller telescopes. The costs of the entire infrastructure of Kitt Peak must be reduced.

At present, the distribution of observing runs at the NOAO 4-meter telescopes is sharply peaked at three nights. Such a distribution function may be the one that maximizes the number of astronomers who use the telescopes in a hands-on fashion. However, it is not the distribution function that will maximize the scientific productivity of the telescopes. Short runs of instruments and exclusively short observing runs increase costs for supporting observers, instruments, and telescopes. Dedicated instruments on telescopes and key program collaborations will reduce operations, instrument maintenance, and travel costs. The panel recommends a broader distribution of observing run lengths, ranging from longer runs to observations that are much shorter in time but have better frequency coverage, such as an hour a night for several days or weeks.

KPNO should strive to provide scientific access to its telescopes through queue-scheduled and remote observing for observations requiring short allocations of telescope time, and should restrict hands-on use of the telescopes mainly to longer observing runs. The experience with the ARC telescope is worth watching; it may demonstrate that remote observing through wideband telecommunications links can be very efficient. Since NOAO must develop the technical infrastructure to support remote observing at both Gemini telescopes, it should be able to provide similar capabilities for the telescopes at KPNO.

The WIYN experience has shown that Kitt Peak can deliver excellent seeing, and KPNO should strive to support programs that take advantage of this capability to provide scientific capabilities complementary to observations by Gemini North. Toward this end, it may be wise for KPNO to close its smaller telescopes, such as the 2.1-meter, the 1.3-meter, and the 0.9-meter telescopes, especially if they can be replaced by a modern 2-meter-class telescope. If in fact the operations costs of WIYN are as low as they have been estimated to be, it would be sensible to consider replacing the existing 4-meter telescope by a twin of WIYN.

However, the fact remains that KPNO does *not* provide unique access to the northern sky for the majority of U.S. astronomers. In a severely constrained budget, keeping KPNO open must be given lower priority than maintaining CTIO. Of the existing telescopes on KPNO, WIYN is clearly the highest priority. If budgets force a cutback of operations on KPNO, some of KPNO's current users will lose their access to telescopes.

Instrumentation

The panel identified the following guiding principles:

- New-technology telescopes and their instruments are increasingly interdependent. Special-purpose telescopes with dedicated instruments are highly efficient.
- Time trading with non-NOAO telescopes, leading to less duplication of instruments, will save costs and enable a more efficient distribution of run lengths.
- A core group of engineers and instrument scientists must be retained near each NOAO site. This staffing is necessary independent of how the facility instruments are acquired.
- Facility instrument development should be science-driven, rather than engineering-opportunity-driven.
- It is healthy for the field to support a wide range of instrumentation (and observing) styles, from experimental to user-friendly. NOAO should incorporate the best ideas and technologies in its facility instruments, whether built in-house or externally.
- Facility instrument development might proceed via cooperative agreements that guarantee some telescope time. Initial science operations could involve key programs open to the community.
- NSF support of students should emphasize involvement with instrumentation development at the expense of training users.

Detector Supply

Applications of large-array technology to OIR instrumentation continue to generate new instruments with corresponding science opportunities. Fundamental advances can be made with innovative instruments on telescopes of all apertures. For the first time in the history of astronomy, nearly all the photons in the focal plane will be effectively used, and even modest-size telescopes, properly instrumented, can make important contributions.

A common problem for both national and private observatories is large detector array development and supply. The special requirements of OIR astronomy dictate detector specifications vastly different from the specifications for non-astronomical uses. Opportunities for collaboration among observatories, instrument builders, and space astronomy missions should be exploited. Detector and readout technology sharing and transfer are already in place in OIR astronomy, and NOAO has played a major role in this process.

Adaptive Optics

Some of the greatest scientific gains in OIR astronomy will come from achieving near-diffraction-limited image quality, using single telescopes and adaptive optics and distributed arrays. Therefore, NOAO should look for opportunities to purchase such technologies for their telescopes as they become available.

The Development Process

What is the best way to develop innovative and effective OIR instrumentation? The process works best when directed by a scientist with a strong motivation to use the instrument to do his or her own science. Access to telescopes for testing is necessary. Innovative instruments do not usually come into being because of a diffusely perceived need. Rather, innovative instruments are most often developed to address a particular problem in science. The motivation comes from individuals with the freedom to design and build leading-edge and experimental instruments.

Who Should Build the Facility Instruments for NOAO Telescopes?

The best, most innovative, and most productive instruments should be supported regardless of origin. NOAO should seek opportunities to leverage NSF support with nonfederal funding to provide facility-class instruments for its telescopes. Groups would receive guaranteed time in addition to partial funding in exchange for delivery of a facility-class instrument that would become available to the community. Such arrangements should be regarded as collaborations between NOAO instrument scientists and engineers and those outside NOAO, rather than as subcontracts. Without an in-house champion, no instrument will succeed. Therefore, it is important that NOAO staff, together with the user community, maintain a strong say in what instruments are "right" for NOAO telescopes.

Such collaborations are currently under way, but the community may not recognize them as such because they have come from individual contacts rather than a community-wide announcement. NOAO should actively encourage any sort of proposal to provide instruments and should inform the community of its intent to do so.

Ranking high among the many benefits of such arrangements would be new opportunities for involving graduate students in instrument development. One example of a model for future instrument development is the Fabry-Perot instrument built at Rutgers University and used extensively at CTIO. It is important that the universities maintain instrument development capabilities, since the universities are where graduate students are trained.

NOAO should take advantage of the opportunity to tap a much larger pool of experienced instrument builders across the nation. There are a number of physics, astronomy, and space science research laboratories well equipped and experienced in sophisticated astronomical instrumentation. By inviting these institutions to collaborate in major instrument developments, NOAO can ensure that each project has a focused, dedicated team of scientists and engineers, and will be able to provide leadership in instrument development in a constrained budget environment.

The panel is concerned that NOAO Tucson operations may be too large and ineffectively utilized, and may have the wrong mix of personnel. The panel examined the NOAO Engineering and Technical Support Division and found that the number of engineering projects currently exceeds the number of instrument scientists, creating a pileup of projects for certain staff. For the FY 1993 to FY 1994 period there appeared to be an imbalance between the number of optical and infrared projects, and there was no clear user pressure for some projects. The panel found no consistent records of true project costs and personnel utilization within the Tucson office of NOAO; this was particularly true of KPNO and the Central Services at NOAO headquarters.

More rigorous project management tools should be used to track costs and schedules of NOAO departments. The panel recommends that a reorganized NOAO make use of focused teams of scientists and engineers to work on a given project from conception to completion. (The panel found examples of this team approach in two new autonomous teams: the GONG group of NOAO and the engineering group of the international Gemini project.) Focused teams will be particularly useful in collaborative instrumentation projects and should further improve the accounting of project costs. It would be helpful to identify a "customer" for each new instrument before development.

Finally, the panel found evidence for a wide range of motivation among the service, engineering, and scientific staff. The newer staff appeared overworked (very common in national laboratories in this transition period). Without reorganization, these problems will only become worse in the Gemini era.

The most successful cases of instrumentation development at NOAO can be traced to good teamwork. Examples are the teams that developed the Hydra multifiber spectrograph and the infrared cameras. The IGP engineering group operates very effectively in this way. NOAO might do well to emulate the IGP's most successful teams in all the NOAO engineering programs.

NOAO should consider contract engineering firms as an alternative source of engineering support to replace a fraction of its present engineering and technical staff. Supplemental engineering talent could be brought in as needed for Gemini instruments, for example, as those instruments will be bid in an open competition and will bring their own funding.

In any case, an engineering and scientific core must exist within NOAO to, at a minimum, sustain the telescopes, the control systems, and instruments, and to help set specifications and see that they are met for facility-class instruments. Access to engineering time is crucial, whether the instrument is built inside or outside NOAO.

NOAO should concentrate resources for in-house instrument development to build on its current strengths, with a focus on detectors, controllers, and fibers. Telescopes need *large* formats in the optical and infrared, especially given the clear needs for wide-field imaging. NOAO should play a role in Gemini instrumentation development.

Both KPNO and CTIO should, whenever appropriate, build their instruments in collaboration with outside groups.

Looking toward the future, and to maximize efficiency, NOAO should actively explore time trading and dedicated facility instrument collaborations with private observatories that have new-technology telescopes. In the best scenario, time trading could result in a net savings for the NSF, better science, and reduced operations and maintenance costs.

Data Analysis Software

NOAO has performed an extremely important service in the development and maintenance of the IRAF image data analysis software system, which has become the most widely used international standard for astronomical data analysis. However, IRAF was written in a fashion that makes it difficult for outside groups to contribute original code; the result is a product that is too dependent on the programming staff in Tucson. The IRAF development did not take full advantage of the very considerable software expertise outside Tucson. The panel encourages NOAO to consider the development of the next generation of data analysis software, but this time to develop a more open system with stronger community participation in the project.

Observer Support

Finally, in order to ensure that astronomers who win time on NOAO telescopes have a minimum level of support necessary to carry out their proposed science, the panel recommends that NSF give NOAO the responsibility and the necessary funds to support travel, lodging, and publication costs of observers who win time at NOAO facilities but lack other sources of support.

Summary Recommendations for NOAO

The panel repeats its main recommendations for the future role of NOAO as the Gemini era approaches. These recommendations are appropriate no matter what the future budgets may be.

Role of USGPO

- U.S. user interface
- Technical support for observing
- Liaison with IGP
- Performance optimization of Gemini telescopes
- Support for Gemini instrumentation development

Role of CTIO

- Support for visitors at CTIO telescopes and Gemini South
- Performance optimization and operation of Gemini South and telescopes on La Serena and Cerro Pachon
- Development of some instruments
- Development of a new-technology 3- to 4-meter-class telescope

Role of KPNO

- Support of visitors at KPNO telescopes
- Performance optimization and operation of several telescopes, especially WIYN
- Development of some instruments

Role of NOAO Tucson

- NOAO administrative headquarters
- Community user interface and service, including wide-band links
- Coordination of north-south and Gemini-KPNO-CTIO observing programs
- Targeted facility instrument production

In a constrained budget environment, it is impossible to maximize the opportunities for scientific leadership, both in the excellence of facilities and in the scientific productivity of those facilities, without sacrificing something. NOAO should not attempt to satisfy all the diverse observing requirements of the nation's astronomers. Nor should it attempt to serve the maximum number of astronomers that its facilities will bear. It is likely that in a scientifically optimum strategy, the annual number of hands-on users of NOAO facilities will decrease, and so the competition for time on NOAO facilities will become even more severe. **In the panel's view such a strategy for NOAO's role is the only way to ensure that astronomers who win time on NOAO facilities will be using the best facilities in the world, and to their best advantage.**

There may be a way, however, for all U.S. astronomers to retain access to a broad spectrum of observing options even as NOAO becomes more narrowly focused. For a possible means to achieve this, we turn to the independent observatories, discussed in the following section.

V. INSTRUMENTATION AT INDEPENDENT OBSERVATORIES

Background

As described in Section II, in "Current Resources for OIR Astronomy," the independent observatories control more than three-fourths of the major telescope assets available to U.S. astronomers, and this situation will prevail for the foreseeable future. Thanks to efforts by visionary astronomers and to the generosity of individuals, foundations, and state governments, U.S. astronomers have the capacity to carry out far more research in OIR astronomy than can be supported by NSF funds alone.

New technologies offer opportunities to increase the performance of all telescopes by huge factors at relatively modest cost compared to that of the telescopes themselves. The cost of these new instruments is not trivial, however. A major facility-class instrument, such as a multiobject spectrograph, can cost several million dollars. As adaptive optics technology becomes more mature, the panel foresees a widespread demand to implement this technology to improve the performance of many major telescopes.

Many independent observatories lack the financial resources to equip their telescopes with instrumentation that will enable the telescopes to perform at their full potential. In many instances, NSF investment in instrumentation for independent observatories will be the most cost-effective way to achieve specific goals of OIR astronomy. **A modest increment in NSF's astronomy instrumentation budget is reasonable given the $300 M of state and private capitalization for the new large telescopes.**

To estimate the net cost of providing modern instrumentation for telescopes at the independent observatories, one can assume conservatively that every such telescope listed in Table 1 should be equipped with one new facility-class instrument every five years, and that the average cost per instrument will be $2 M for telescopes of aperture 2 to 5 meters and $5 M for telescopes of aperture greater than 5 meters. (This estimate is consistent with one made by a group of observatory directors at a recent meeting.) The calculation yields a net funding rate of $12.4 M/year. Assuming that the independent observatories share roughly 30% of the costs on average, a very strong scientific case exists for NSF to support the development of such instruments at a level of about $9 M per year. Such a funding level would vastly increase the scientific productivity of the nation's telescopes.

In a constrained funding environment, it is unrealistic for the NSF Division of Astronomical Sciences to provide such a funding level, especially in view of the need for funding Gemini operations and modernizing the telescopes at NOAO, and for NOAO to provide a broad spectrum of observing options to the nation's astronomers. Indeed, the panel cannot realistically expect NOAO to meet these demands in any case. As has been discussed, to maintain scientific leadership within a constrained budget, NOAO must narrow its focus to those activities it can do best. If it does so, the panel must then ask: Is there another way to provide some of the observing options that NOAO must curtail?

A New Program for Instruments at Independent Observatories

For the above reasons, the panel recommends that **the NSF Division of Astronomical Sciences establish a new program to provide instruments at independent observatories that agree to provide national peer-reviewed access to their facilities in proportion to the funds provided.**

The proposed facility (including possibly an instrument, a mirror, and/or a telescope) must leverage substantial nonfederal investment, which may be in the form of existing telescopes built with nonfederal funds and/or cost sharing with nonfederal funds.

NSF funds must be used only to provide capital equipment that will directly augment the scientific performance of the telescope. The panel does not recommend that NSF provide funds for operations or maintenance of independent observatories. That would only create a dangerous incentive for independent observatories to begin counting on the NSF to make up for inadequate fiscal planning.

This program should be distinguished from the ATI program. In such a program, it is often impossible to predict that a given effort will yield a working device, which would probably not be suitable for general use in any case. In contrast, the instruments to be funded under the program the panel recommends should have a reasonable expectation of providing important and reliable observational capability, based on prior successful experience with similar instruments. Of course, there is a continuum between ATI and the development of facility instruments. It would be inappropriate to rule out some level of innovation and risk in the latter. Therefore, ongoing judgments will be required to determine whether the proposed facility instrument meets the "reasonable expectation" criterion. A mechanism to make such judgments is suggested in the subsection "Review of Proposals for Instrument Development" below.

This program should be regarded as experimental, and its growth or termination should depend on scientific performance. Appropriate indicators of performance are (1) the quality of the science produced, by astronomers at the host institution and by external users, as a result of the program; (2) the number and quality of proposals to build new instruments; and (3) the intensity and quality of the competition for national access to the facilities.

The panel believes that an appropriate level of NSF support for this program is about $7 M/year. In fact, the NSF already supports the development of OIR instrumentation through its grants program, at a current level of about $7 M/year (Section II). Most (about 75%) of the NSF funding for OIR instrumentation has been devoted to the development of advanced technologies, such as adaptive optics and interferometry. Funding of these activities was highly recommended by the AASC report, and this panel recommends that NSF continue to fund such programs aggressively with no strings attached. However, some (about 25%) of the ATI funding of OIR astronomy has been used to build facility instruments and telescopes at independent observatories. The panel recommends that this fraction, about $2 M/year in 1993, be removed from the ATI program and augmented by approximately $5 M/year of new funds in the NSF Division of Astronomical Sciences budget to meet the recommended funding level of the new facility instrumentation program.

The panel suggests that NSF implement this program immediately, beginning with a portion of existing funding in the present ATI program and augmenting the program as rapidly as the availability of new funds permits. Since the scheme for national access is untried, we need to gain some experience to know whether it will in fact deliver excellent science at low cost. If the program can provide a broad and growing range of observing options to all astronomers through its provision for national access, the need for NOAO to provide such a range of options on its own facilities will diminish. This scheme might create an environment in which all observatories can realize cost savings by specializing their facilities. The need for immediacy arises from the fact that there is a window of a few years before NSF must provide its full share of Gemini operations costs. At that time, NSF and NOAO may have to make hard choices regarding priorities for facilities. These choices might be more optimal if they could be made on the basis of some experience with the new instrumentation program.

Guidelines for National Access

The goals of the national access provision are (1) to ensure that the program yields the best science, (2) to provide national access to a broad range of observing facilities, and (3) to realize the cost savings that may accrue from efficient modes of operation of independent observatories. To achieve these goals, the panel proposes the following guidelines.

First, the conditions for national access must be flexible and responsive to the operating constraints of each participating observatory. Any provisions requiring substantial changes in operations will drive costs up and will be a deterrent for that observatory to participate in the program. Therefore, in the first instance the participating observatory should propose its own provisions for national access so as to minimize the impact on costs. In an optimum system, the possible modes of national access might vary widely from one observatory to another. For example, one observatory might elect to provide only "data on demand," through queue observing by its own staff. An observatory equipped for remote observing might provide that option. Another observatory might elect to provide hands-on training of students by its own staff, and another might support long-term projects by experienced astronomers. Of course, observatories could also choose to provide any combination of the services listed above (or others not listed).

A mechanism is needed to ensure that the aggregate of participating observatories will meet national needs for a variety of observing facilities and modes. It is important for each participating observatory to understand whether its provisions for national access are responsive to unfulfilled needs. Since NOAO already has responsibility to provide national access, and much experience in doing so, NOAO might undertake the responsibilities to provide this information and work with proposing observatories toward an optimal balance of options to the national community. The proposing observatories would be able to discuss their provisions for national access with NOAO before submitting their proposal, and perhaps modify these provisions to be more responsive to unmet needs as appropriate.

The primary goal of the program is to enable excellent science, for both the astronomers at independent observatories and those without access to their own facilities. Therefore, the fraction of telescope time provided for national access by participating observatories should be proportionate to the NSF funds provided for new instrumentation, as a fraction of the amortized capital cost of the nonfederal facilities. If the fraction were greater, that would remove the incentive for many of the best independent observatories to participate and the program would not yield the best science. If less, the program would not meet the national need for access to a broad spectrum of observing options.

The principle of proportionate access and how much national access time the program might deliver can be illustrated by two hypothetical examples. First, suppose that an independent observatory has built a modern 3.5-meter telescope, at a net capital cost of $15 M, and submits a proposal to NSF for funding to build an instrument costing $3 M. Suppose that the observatory wishes to discharge its obligation to provide national access over a period of six years. Assuming that the telescope value decreases exponentially with a mean life of 20 years, the net depreciation of the telescope during the first six years would be $3.9 M. Suppose further that the annual operating costs are $1.5 M. Then, the net cost to the observatory for the first six years would be $12.9 M. Then, a reasonable fraction of telescope time to provide for national access would be ($3 M)/($12.9 M) = 0.23, or about 85 nights per year for six years.

As a second example, suppose that the Keck Observatory submits a proposal to NSF for $4 M to support in part the construction of a new instrument and wishes to discharge its obligation for national access in four years. Then, assuming a capital investment of $80 M, a mean life of 20 years, and operating costs of $6 M/year, a similar calculation yields 38 nights per year of national access to Keck for four years. However, in this case a further correction is warranted because the OIR astronomers at the California Institute of Technology and the University of California system already represent a significant fraction (about 15%) of the active OIR astronomers nationwide. Since it would be awkward for these astronomers to apply for national access time on their own telescope, it would be appropriate to reduce the national access time by a factor of 0.85, giving a final result of 32 nights per year for four years.

Additional examples of sharing are the Sloan Digital Sky Survey and 2MASS. These are projects currently being undertaken by university consortia to produce large-scale photometric and spectroscopic surveys using special-purpose telescopes and instruments. In these examples, the national benefit is open access to extraordinarily powerful and unique databases. Such arrangements would be attractive to the owners of the telescopes if they were to individually reap more, not less, high-quality data by participating in such a program. That may be true in many cases, because modern instruments with wide fields can often provide major gains in telescope efficiency. For such a scheme to be acceptable to the community, it is also essential that *new funding*, not repackaged funding, be used to initiate this program.

An instrumentation program funded steadily at the recommended level of $7 M/year would provide for national access the equivalent of 85 nights per year of Keck time plus two modern 3.5-meter telescopes full-time. (In fact, the aggregate program might yield a richer mix of observing options.) This program could significantly alleviate the current shortage of access time to well-equipped telescopes. The national access time provided would not be the only scientific benefit of the program, however. Additional scientific benefit would result from the increased observing power that would accrue to the independent observatories.

These hypothetical examples are intended not to serve as specific guidelines, but rather to illustrate the principles by which a reasonable amount of national access might be calculated. The program will probably work best if participating observatories are free to propose any provisions that they see fit. For example, an observatory may wish to propose a mix of observing options on a variety of its telescopes. The panel believes that the review process would provide sufficient incentive for participating observatories to offer a reasonable amount of national access time on their facilities.

Since each national access arrangement would carry administrative and other costs, there would be a threshold instrument cost below which the benefits of national access are not sufficient to justify incurring these costs. This threshold might be in the range of $0.5 M to $1 M, depending on circumstances. A flexible mechanism for determining this threshold is suggested in the next subsection, "Review of Proposals for Instrument Development."

The proposed terms for national access, including a plan for user support, would then become part of the proposal to NSF for the new instrument. The proposal should then be judged on overall scientific merit, with criteria including (1) the value of the science enabled for both the host observatory and national users, (2) the scientific leverage provided by nonfederal cost sharing, and (3) the extent to which the proposed instrument meets an unfulfilled scientific requirement.

Finally, the panel recommends that the national access time provided by the participating independent observatories be distributed through a national time allocation committee (TAC). Of course, before the TAC meets, the independent observatories should screen proposals to use their facilities, just as NOAO does. The TAC will need to know whether the proposals are suitable for that facility and the reasons, technical and otherwise. A national TAC would have the following advantages: (1) it would ensure that the national access time is granted on the basis of scientific merit alone, as determined by competitive peer review; (2) astronomers could propose to a single agency, according to a standard format; (3) if a proposal were found to be scientifically excellent but unsuitable for a given observatory, the TAC could attempt to identify an alternative facility; and (4) a single TAC would probably be the most efficient procedure.

The proposed program would have at least one significant new advantage for the science that could be carried out: it would greatly simplify and streamline programs of coordinated or synoptic observations. Many such programs arise in OIR astronomy, from studies of time-variable phenomena and periodicity searches, and in particular observations coordinated with spaceborne observatories (such as HST, ROSAT) for which increased longitude coverage is often crucial. A national TAC could consider proposals for near-simultaneous or sequential use of several large telescopes that would otherwise be unlikely to be scheduled separately for a single program.

This qualitatively new observing capability might also justify modest NASA support for such programs, or the instruments to carry them out, as suggested in Section VI.

Review of Proposals for Instrument Development

The panel also recommends that **proposals to NSF for grants for instrumentation development (both facility instruments and advanced technology instruments) should be selected on the basis of an annual review by an NSF jury committee.** The panel believes that such a process, details of which are described below, would be an effective mechanism for optimizing the scientific benefits of NSF funding of instrument development. The jury committee would review and seek to coordinate instrumentation plans at NOAO, the independent observatories, and the collaborations of outsiders with NOAO.

There are two major advantages to a jury review. First, it solves a problem raised by a number of correspondents—namely, that they cannot make informed judgments when reviewing a proposal for instrumentation because they do not have a clear understanding of the global context. A given program may be fine technically, but it is difficult to assess whether it is the scientifically most valuable one relative to other alternatives. Second, and perhaps most important, a jury review provides a powerful educational forum for all participants, which could accelerate technology development and encourage cooperation where appropriate. Indeed, the jury committee should search for economies of scale and opportunities to avoid duplication of effort, especially in instrument subsystems (e.g., controllers, detector arrays). Perhaps the greatest benefit of such a review committee would come not in the judgment of the proposals at hand, but in the guidance provided for future instrument development.

In addition to determining the scientific merits of the proposed instruments, the jury committee might be able to advise NSF whether a given instrument proposal should be regarded as an ATI program item or a facility-class instrument. If the latter, the committee must further decide whether the proposed instrument meets the cost threshold for national access, and whether the national access provisions are equitable, according to the principles described in "Guidelines for National Access" above.

VI. PROGRESS WITHIN A CONSTRAINED BUDGET

Overview

Here the panel summarizes its major recommendations and states priorities for NSF funding of OIR astronomy. In doing so, the panel is mindful of the uncertain prospects for growth of the NSF astronomy budget. The panel is confident, however, that the enormous recent increase in the power of ground-based OIR telescopes to enable major advances in our understanding of the universe, together with major capital investment in new telescopes, both national and private, makes a strong case for a modest increase in the NSF astronomy budget.

The panel recommends a strategy in which NSF can, over the next several years, increase its annual funding of OIR astronomy by approximately $10 M in 1994 dollars. This increase is essential to properly support Gemini, the instrumentation program for national and private observatories, and the continuation of a strong program at the existing NOAO facilities. With this increment, NSF funds would be leveraged by the enormous nonfederal investment in OIR facilities in the past decade, allowing these new telescopes to reach their full scientific potential while providing access for *all* astronomers.

If such a boost to the NSF's astronomy base budget is not possible, then first priority must go to support of the Gemini operations. If no additional funding is added to the astronomy base budget, then the initiation of Gemini operations would have to come at the expense of other existing national OIR facilities, particularly those that are the least unique. This allocation of resources would cause many excellent astronomers to become disenfranchised, the field would suffer from the loss of their expertise, and educational opportunities for future generations would be diminished.

Section IV above details recommendations for a new strategy for the operation of NOAO, which the panel recommends regardless of the budget future. The general recommendations below are a restatement of many of these guiding priorities.

No-Growth Scenario

If the NSF Division of Astronomical Sciences must operate under level funding, even with the completion of the Gemini telescopes, then there will be no alternative to a major cutback of operations and closing or privatizing of existing facilities. Gemini will be a leading scientific facility and is an international commitment that must be supported.

In this no-growth scenario, NOAO must absorb the full \$8 M U.S. cost of the Gemini project (including both the \$5.5 M for the U.S. share of IGP operations and the \$2.5 M cost of providing the resources for U.S. access to Gemini).

Given the unique access to the southern skies offered by CTIO, and the duplication of many of KPNO's capabilities in the independent observatories in the Northern Hemisphere, higher priority must be given to continued operations at CTIO. At KPNO, the WIYN telescope and limited operations of the 4-meter telescope could continue, but probably all other telescopes, as well as the bulk of the support operations in Tucson, would likely have to be closed. Whatever remained open at KPNO would have to operate with a reduced support staff, in a much less hand-holding mode of operation. The central services provided by NOAO to its three observatories, KPNO, CTIO, and NSO, would effectively cease.

NOAO would have to sharply restrict its instrumentation program. Moreover, it would be impossible for NOAO to build any new-technology telescopes, even through partnerships. Astronomers who depend on KPNO would find that their access to telescopes would be sharply curtailed and the competition much more intense than it is now. An example of collateral damage under this scenario is that science education at universities would suffer because many professors would not be able to maintain and engage students in active research programs in OIR astronomy. Another major casualty would be the loss of the internship program for undergraduate and graduate students.

The panel's priorities for NOAO operations are clear:

1. Gemini operations,
2. Continued operations at CTIO,
3. Operations of WIYN,
4. Continued operations of the 4-meter telescope at KPNO,
5. Other unique instrumentation development at Tucson, and
6. All other NOAO operations.

In a very limited budget, the panel recommends cutting from the bottom of this list while preserving the functions above. (Instrument upgrades are implied in priorities 1 to 4.) Uniform cutting of all services now provided by NOAO is specifically **not** an acceptable option. The panel estimates that even in the worst budget situation, NOAO would have sufficient funds for priorities 1 to 4.

The panel appreciates that substantial savings cannot be made simply by closing small telescopes, as these facilities cost very little to operate. Only by closing or drastically scaling back an entire observatory can one expect to save funds of the magnitude required in a flat-budget scenario. The panel's priority is to keep the unique facilities open if at all possible, and to concentrate cutbacks on the downtown Tucson operations, while at the same time reducing the personnel at KPNO to a minimum level. Such cutbacks would come at a scientific price, such as the loss of capacity to immediately repair equipment that fails for one reason or another. (Scheduling of longer runs and service observing can mitigate this loss, however.) In any case, it is better to have limited service than no service at all. The panel is further mindful that telescopes other than those owned by NOAO operate on Kitt Peak and also benefit from the infrastructure provided by NOAO. The panel, under even the worst budget scenario, does **not** recommend that KPNO be closed.

Beyond stating these scientific priorities for NOAO, the panel does not attempt to provide a detailed road map or model for NOAO to reduce operations costs as required. That is the proper responsibility of NOAO management.

With a truly flat budget, NSF would not be able to provide new funds for facility instruments at independent observatories, but would need to initiate the new program at a modest level within the existing budget of the NSF instrumentation grants program. The national access to independent observatories enabled by this funding level would not begin to substitute for the loss of access at KPNO.

Finally, in this scenario, the sharp reductions in activity at KPNO and in the level of support of engineering and technical services, and the overall pressures on the NOAO budget, would be certain to have a negative impact on support for the scientific activities of the National Solar Observatories.

Minimal Growth Scenario

If NSF can increase its annual funding for OIR astronomy by part, but not all, of the $10 M recommended, the panel envisages continuing fierce competition for resources between the independent observatories, which need instrumentation funds, and NOAO, which must provide the U.S. interface to Gemini, support its observers, and strive to maintain scientific leadership in some areas. How should NSF decide to distribute its limited funds in the face of such competition?

The first priority of any boost to the NSF astronomy base budget must go to Gemini operations, as discussed above. Any boost beyond the amount payable to IGP operations would be available for the facility instrumentation program at the independent observatories outlined above.

Although funding of IGP operations will not rise to the stationary level until 2003, the panel recommends an immediate boost to the NSF astronomy base budget to allow augmentation of the facilities instrumentation program outlined above. This would give the NSF time to judge the effectiveness of the program and to make mid-course corrections, if needed, well before Gemini operations begin.

Modest Growth Scenario

In a modest growth scenario, the panel assumes that, by 2003, NSF will be able to augment its annual budget for OIR astronomy by $5.5 M to cover the U.S. obligation to the IGP, so that NOAO funding can remain level in constant dollars. Second, the panel assumes that NSF will be able to augment its annual budget for facility instruments at independent observatories by $4.5 M/year, beginning almost immediately. Thus, the panel assumes that NSF will be able to increase its net annual funding of OIR astronomy by approximately $10 M by 2003.

With such an increase, the nation would have a very healthy and productive infrastructure for OIR astronomy. The panel believes that NOAO can ensure that the United States will gain full scientific value from the Gemini telescopes and assert leadership in OIR astronomy. To do so, NOAO must further focus its resources on Gemini science and other areas where it can excel. As discussed above, even in this optimistic scenario NOAO cannot satisfy all the diverse needs of the nation's astronomers, and competition for time on NOAO telescopes may become even more intense. However, with bold and frugal management, combined with external partnerships, NOAO will be able to exert leadership in instrumentation and will have a good chance to replace some of its older telescopes with powerful, well-instrumented new-technology telescopes.

Great scientific leverage will result from the augmented program to fund facility instruments for powerful new telescopes at independent observatories. Moreover, the national access time provided to astronomers through this program should mitigate the loss of observing options to astronomers who now depend primarily on NOAO for access to telescopes. These astronomers would enjoy a net gain in observing time and options if this program can be funded fully.

The strategy for growth recommended here is not lavish. The panel makes no recommendations for major new facilities that have not already been recommended by the AASC report and, in fact, are already under way. The $5.5 M cost to support operations of the IGP is modest given the $88 M capital investment by NSF. With level funding (excluding the IGP operations costs), NOAO management will be challenged to take on the new responsibility of the U.S. interface to Gemini, to build new facilities, and to maintain scientific leadership. The only new program recommended is the $4.8 M augmentation for instrumentation at independent observatories. That is conservative, too. The scientific opportunities presented by the new telescopes at independent observatories could easily justify a much greater investment by NSF.

Support of Space Astronomy Missions

The national time allocation committee that the panel recommends would enable astronomers to carry out, often for the first time, powerful coordinated and synoptic observing campaigns in support of space observations. Such programs are likely to spawn demand for new instruments (e.g., common, if not similar, imagers or polarimeters) on several telescopes so that data can be optimally matched. To realize these benefits, the panel recommends that NSF continue to work with NASA to develop a coordinated strategy for support of space astronomy missions by ground-based OIR telescopes. It would be appropriate for NASA to support a share of costs for instrument support and observer access in proportion to the annual national use of telescopes (national or private) in support of space observations.

Summary

The panel has outlined above three possible futures for OIR astronomy in the coming decade.

- In the most pessimistic scenario the panel recommends that the above listed cutbacks be applied to current NOAO operations in order to fund the Gemini operations.

- The panel strongly recommends that the NSF increase the base funding of the Division of Astronomical Sciences in order to cover the $5.5 M U.S. contribution to the international Gemini project operations budget.

- In a modest growth scenario, the panel recommends a $10 M/year increase to the astronomy base budget, which would support both the Gemini operations and the new facilities instrumentation program for the independent observatories.

Without a boost to the NSF astronomy base budget, the initiation of Gemini operations will force the closure of productive NOAO facilities now in operation. This would be a great shame and a waste of productive facilities and talent. The loss of national access to telescopes would also be harmful to U.S. higher education in science. Given the huge investment in space-based facilities by NASA and the investment by nonfederal sources in other ground-based telescopes, the recommended $10 M/year of additional NSF support for OIR astronomy is a very modest amount of money. Yet without it neither the NASA investment in space facilities, nor NSF's investment in Gemini, nor the investment of the private observatories in their new facilities will reach their full scientific potential.

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