National Optical Astronomy Observatories

LONG RANGE PLAN

FY 1989 - 1993

4 April 1988
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1. INTRODUCTION AND PLAN OVERVIEW

The three decades that have passed since the founding of AURA have been a remarkable period in astronomy. Quasars, pulsars, and the cosmic background radiation were all discovered since 1960. Access to space has led to the opening of the x-ray and gamma ray windows. Infrared astronomy, first on the ground and then in space with the IRAS satellite, has revolutionized our view of star formation, of the structure of the interstellar medium, and of the energetics of active galaxies. There have been voyages of discovery to the planets and to Halley's comet. With the measurements of solar neutrinos and oscillations, astronomers have developed diagnostic tools that allow them to probe the interior structure of the Sun.

There is no evidence of a slackening in the pace of growth of knowledge of the universe. During the next decade and a half we can expect to see the launch of the Hubble Space Telescope and of long-lived observatories for gamma ray, x-ray, and infrared astronomy. These facilities, combined with immensely more powerful ground-based telescopes, will provide the tools necessary to resolve, or at least to begin to resolve, the fundamental questions raised by the many discoveries during the past thirty years. What is the large scale distribution of matter in the universe? To what extent does luminous material trace the distribution of matter? Did galaxies all form at about the same time, or are there young galaxies relatively nearby? Once formed, do galaxies evolve at a uniform rate, or does the pace of evolution depend on local conditions? What is the nature of the engine that powers the emission from quasars and active galaxies? What triggers star formation? What determines the initial mass function, the frequency of binary and multiple systems, and the conditions under which planetary systems result? How well do models represent the detailed interior structure of the Sun, and to what extent must stellar models be modified to reflect the detailed knowledge now being acquired from solar observations?

We cannot anticipate, of course, the discoveries of qualitatively new phenomena that will inevitably occur during the next several years. What we can anticipate is that we will achieve an understanding of the origin and evolution of galaxies and of clusters of galaxies that is on as firm a footing as the understanding of stellar evolution is now. We can anticipate that the understanding of stellar evolution will prove to be on a far less firm footing than we thought it was. We can also anticipate that ground-based observations will continue to play a central role in astronomy. The high density of spectral information in the optical and infrared regions of the spectrum makes this often the wavelength region of choice for analyzing the dynamics, physical conditions, and compositions of astronomical objects. Increasingly, however, the objects studied are selected from surveys carried out at very short or very long wavelengths. These objects may be quite faint in the optical and ground-based infrared, and so the demand for larger telescopes and more powerful instrumentation will only accelerate.

In order to meet this demand, many groups are planning to build major new optical telescopes. A summary of this activity is shown in Table I. Specifically, the European Southern Observatory has received funding approximately equal to $240 million to construct an array of four 8-m telescopes in Chile. This situation stands in strong contrast to the situation of NOAO, the U.S. counterpart to ESO. Not only is funding not assured for new telescopes, and cannot be available before the early 1990s, it is far from clear that support for the technology development that must precede construction will be adequate to guarantee that we are ready to proceed at the fastest possible pace when funding does become available.
# Present Plans for Large Telescopes

<table>
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<tr>
<th>Organization</th>
<th>Name</th>
<th>Size(m)</th>
<th>Location</th>
<th>f/#</th>
<th>Mirror Type</th>
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<tr>
<td>1. CalTech/UC</td>
<td>Keck</td>
<td>10</td>
<td>Mauna Kea</td>
<td>f/1.75</td>
<td>Segmented</td>
<td>Zerodur</td>
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<tr>
<td>2. Europe/ESO</td>
<td>(VLT) Very Large Telescope</td>
<td>4 x 8</td>
<td>Chile (Paranal?)</td>
<td>f/1.8</td>
<td>8m Meniscus</td>
<td>Zerodur</td>
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<tr>
<td>3. Japan</td>
<td>(JNLt) Japanese National Large Telescope</td>
<td>7.5</td>
<td>Mauna Kea</td>
<td>f/2</td>
<td>8m Meniscus</td>
<td>ULE</td>
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<td><strong>Projects in Advanced Planning Stages</strong></td>
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<tr>
<td>4. Carnegie/Hopkins/UA</td>
<td>Magellan</td>
<td>8</td>
<td>Chile (Las Campanas)</td>
<td>f/1.2</td>
<td>8m Honeycomb</td>
<td>BSG</td>
</tr>
<tr>
<td>5. Chicago/Italy/OSU/UA</td>
<td>Columbus</td>
<td>2 x 8</td>
<td>Mt. Graham</td>
<td>f/1.2</td>
<td>8m Honeycomb</td>
<td>BSG</td>
</tr>
<tr>
<td>6. MMT - Upgrade</td>
<td>Multiple Mirror Telescope</td>
<td>6.5</td>
<td>Mt. Hopkins</td>
<td>f/1</td>
<td>6.5m Honeycomb</td>
<td>BSG</td>
</tr>
<tr>
<td>7. NOAO</td>
<td>(EMT) Eight Meter Telescope</td>
<td>2 x 8</td>
<td>Chile (CTIO) + Mauna Kea</td>
<td>f/1.8</td>
<td>8m Honeycomb</td>
<td>BSG</td>
</tr>
<tr>
<td>8. NOAO</td>
<td>(NNTT) National New Technology Telescope</td>
<td>4 x 8</td>
<td>Mauna Kea</td>
<td>f/1.8</td>
<td>8m Honeycomb</td>
<td>BSG</td>
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<td><strong>Projects in Early Planning Stages</strong></td>
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<td>9. Germany</td>
<td>(DGT) Deutsches Gross Teleskop</td>
<td>12</td>
<td>La Palma?</td>
<td>f/1.5</td>
<td>8m + 2m tutu</td>
<td>Quartz</td>
</tr>
<tr>
<td>10. United Kingdom</td>
<td>(UKLT) United Kingdom Large Telescope</td>
<td>8</td>
<td>Mauna Kea or La Palma</td>
<td>f/1.8</td>
<td>?</td>
<td>?</td>
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<td><strong>Unknown</strong></td>
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<tr>
<td>11. USSR</td>
<td>(CBT) Soviet Large Telescope</td>
<td>~25</td>
<td>Central Asia</td>
<td>?</td>
<td>Segmented or Array</td>
<td>Cital</td>
</tr>
</tbody>
</table>
Table I continued

1. The Keck Telescope is funded. The approximate cost is $90M. Construction is underway and the completion date should be 1991.


3. Is expected to be funded on April 1, 1989 after the establishment of the Japanese National Astronomy Observatory on April 1, 1988. Anticipated cost of 7.5-m telescope is approximately $100M. Completion date will be March 31, 1994.

4. Most of the funding is assured. The starting date is closely linked to the borosilicate glass mirror program.

5. Construction of two telescopes; single mount used in the interferometric mode. Some of the funding is assured. The starting date depends on the borosilicate glass mirror program.

6. Will use the first of the large borosilicate glass mirrors. The mirror is expected to be available in 1990.

7. The EMT is to be located one each, in the Northern and Southern hemispheres. Will use the first of the 8-m borosilicate glass mirrors. This mirror is expected to be cast in 1991. The approximate cost will be $45M each.

8. Planning for the long-term future after an 8-m telescope technology has been demonstrated; consists of interferometric array of four telescopes.

9. In the preliminary planning stages. Probably will be located on La Palma.

10. The United Kingdom Large Telescope is in preliminary planning stages. It is to be built, probably in collaboration with European or United States partners.

11. We will call this the Soviet Large Telescope (CBT). Status of development and construction of the CBT is unknown. The telescope will probably be located in the mountains in the southern part of the Tadzhik republic.
Indeed even the continued operation of existing facilities is threatened. In real terms, that is corrected for inflation, the total budget for NOAO is lower than it has been at any time since 1964. In actual dollars, not corrected for inflation, the new funds received from the NSF have been static for the past five years. It is clear that NOAO cannot simultaneously expand support for new initiatives such as technology development for 8-m and larger telescopes and for GONG and at the same time continue to operate all existing facilities. Accordingly NSF and AURA are undertaking a community-wide review to determine which programs within NOAO should be retained and which will no longer be supported with NSF funds. Until that review is completed, there can be no credible long range plan for NOAO.

AURA did recently submit a proposal to the NSF to renew the contract for operation of NOAO. This document repeats much of that proposal since it continues to represent what AURA believes that the National Optical Astronomy Observatories could and should be. Those goals cannot be realized within existing and projected funding levels. Nevertheless, it is important to underscore that failure to achieve the program described in this document will be the consequence of inadequate funding not of a lack of vision on the part of AURA and NOAO. Accordingly, we present here again what we believe is the right path of development for NOAO.

NOAO is responsible for providing nationally accessible ground-based facilities for both solar and nighttime astronomy. It is a large and complex organization, and a long range plan that describes each of its major components even briefly is necessarily long and complex as well. It is important, therefore, to underscore our priorities for the fiscal years 1989 - 1993. It is our intent to continue to operate facilities at all three sites—Sacramento Peak, Kitt Peak, and Cerro Tololo. Continued operation is possible if and only if support for these sites is maintained at least at the level of the FY 1987 program plan. The highest priority for an increment in the core budget is for facilities maintenance. All of NOAO’s facilities are about 25 years old, and priority needs for maintenance can no longer be deferred. The next highest priority in the core program is for a doubling over the period of this plan of the budget for focal plane instrumentation and for the development of technologies such as adaptive optics and interferometry. This increase is necessary in order to allow the aggressive implementation of new array detectors for both optical and infrared astronomy, to develop adaptive optics for solar and infrared astronomy, and to develop new multiple object spectrographs. An investment in new instrumentation would yield a higher scientific return per dollar than any other.

During the five years covered by this plan, NOAO can best serve the astronomical community by continuing the effective operation of existing facilities. In Europe and Japan, however, major investments are being made in the next generation of telescopes for both solar and nighttime astronomy. The U.S. national observatories must keep pace, and accordingly must also, during this five year period, begin to make major investments for the future. The highest priorities for major initiatives are to build 8-m telescopes, with at least one in each hemisphere, and to provide a new facility for high resolution studies of the Sun.

This plan first outlines some of the important advances in astronomy that have been made, at least in part, at NOAO facilities. It then discusses some of the key scientific opportunities for the next several years. It is this analysis that forms the basis for the specific program NOAO proposes in this plan. The succeeding section of the plan describes several initiatives that NOAO wishes to undertake. The next section describes the core programs within each of the four divisions of
NOAO and describes how those programs will evolve. The GONG project and the
development of technology for the next generation of telescopes are included in the
core program. The final section of the plan describes the budget for both the core
programs and the initiatives.

In preparing a plan of this kind one must choose what to emphasize. One can
choose to stress the future. The opportunities in astronomy now available have not
been matched at any time in the history of the field. Advances in observing
techniques and the feasibility of building much larger telescopes are stimulating
innovative thinking and attracting some of the most talented scientists of our
generation. New regimes of high spatial resolution and new precision in
spectroscopy can be attained. It has become possible to attack qualitatively new
kinds of problems ranging from the interior structure of stars to the formation and
evolution of galaxies.

Alternatively, one can choose to emphasize the painful reality of the past few
years. Funding of the national observatories has seriously declined in real terms.
The staff has shrunk, and many highly talented scientists and technical staff have
left the organization. Despite the demand for observing time, there have been no
new facilities built in nearly fifteen years. All of the divisions of NOAO are
dependent on instrumental investments made a decade ago. The support for new
focal plane instrumentation has diminished dramatically in recent years, and U.S.
astronomers are far behind their European colleagues in such areas as multiple
object spectroscopy. It has been nearly ten years since an instrument of the scope
of the 4-m FTS at Kitt Peak has been put into service. Facilities maintenance has
been so long deferred that both the reliability and safety of our operations are
threatened.

In this plan, however, we have chosen to emphasize the future. Only the final
section on the budget addresses the very real problems faced by NOAO because of
funding constraints. The main sections of the plan outline a specific program that
will greatly enhance opportunities for observational research on the Sun, stars,
galaxies, and the interstellar medium, and will permit the National Optical
Astronomy Observatories to play an effective role in maintaining U.S. leadership in
astrophysics. During fiscal years 1989 - 1993, NOAO plans to finish a substantial
portion of the construction of at least its first 8-m telescope, to break ground for
the National New Technology Telescope (NNIT), and to join with a consortium to
build a facility for high resolution studies of the Sun. NOAO also plans to
construct a prototype distributed array to test the technology for infrared and
optical interferometry, to join with universities to add at least one 4-m telescope in
each hemisphere, and to expand the facilities for synoptic observations of both solar
and stellar activity. If NOAO is to meet the challenges of the science, it can
aspire to do no less.
II. SCIENCE AT THE NOAO

Astronomical research is the basic function of the NOAO. New and fundamental insights into the nature of the universe are its "end product." The scope of the research is extremely broad, and Table II shows the growth of scientific publications at NOAO from 1960 through 1986. Over 7,300 scientific papers have been published during that period. In this long range plan, we can only summarize a limited sample of key results in a few particularly active areas of research and indicate some areas where we think the promise of rapid progress is the greatest. It is, of course, this assessment of the future course of our science that influences our priorities for new instrumentation and for major initiatives.

Optical astronomy has undergone a technical revolution in the past few years. The availability of high quantum efficiency solid state detectors has made possible observations of unprecedented depth and sensitivity. For example, when the charged-coupled device (CCD) detector system was placed in service at the KPNO #1 0.9-m telescope in 1982, the telescope became as powerful as the 5-m Hale telescope when it was first commissioned. The use of such detectors at the 4-m telescopes has resulted in a unique ability to look back over a significant portion of the age of the universe. These observations are already having a profound effect on our understanding of the evolution of stars and galaxies and of the origin of the universe itself. Observations of more nearby objects have been greatly enhanced by the ability to detect fainter members of a given class and by the easy acquisition of significantly larger data bases. In the paragraphs that follow we briefly describe some of the major scientific accomplishments made at NOAO in recent years. Many of these were made possible only by use of state of the art instrumentation, and several of them have opened new and significant areas of scientific inquiry.

A. The Large Scale Structure of the Universe

The earliest 20th century cosmologies assumed that the universe is homogeneous and isotropic, and this assumption has persisted until the present. Current theories posit homogeneity and isotropy when averages are taken over a large scale. In recent years, however, observations taken with NOAO and other telescopes have begun to present serious challenges to current cosmological models.

In 1983 R. Kirshner (Ctr. for Astrophysics) and his collaborators used the KPNO telescopes to identify what appeared to be a gigantic void, or absence of galaxies, in the direction of the constellation Bootes. In 1986, this same group used the KPNO facilities to confirm the existence of this void, which occupies a volume of over one million cubic megaparsecs and is roughly spherical in shape with a diameter of about 120 megaparsecs. Also in 1986 V. de Lapparent, M. Geller, and J. Huchra (Ctr. for Astrophysics) published results from the extended Center for Astrophysics redshift survey which showed galaxies residing on the surfaces of contiguous bubble-like structures whose diameters are typically 25 megaparsecs with a maximum of 50 megaparsecs. A similar picture of the distribution of galaxies in space emerges from a 21-cm survey of 2,700 galaxies published in 1986 by M. Haynes (Cornell U.) and R. Giovanelli (Arecibo Obs.). Finally, a group of seven investigators have used KPNO and other telescopes to discover streaming motion of galaxies on an extremely large scale. Their survey of elliptical galaxies has shown a net streaming motion of galaxies over a region about 100 megaparsecs in size, with a velocity of roughly 500 km/sec.
<table>
<thead>
<tr>
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All of these large scale features in the Galaxy population pose severe challenges to current cosmological models. The difficulties lie in the inability of these models to produce such large structures by purely gravitational means. The hot dark matter models use the hot particles to suppress excessive small scale fluctuations, but they require arbitrary normalization to reproduce the galaxy-galaxy correlation function, and they have difficulty producing the giant mass fluctuation required to explain the large scale streaming motion. Cold dark matter models cannot produce the large structures, and they yield too much small scale structure unless *ad hoc* assumptions such as biased galaxy formation are introduced. Non-gravitational theories using shock waves to initiate galaxy formation may provide the observed structure, but they require as yet unobserved explosive events of enormous energy; about $10^{50}$ ergs per event, which is equivalent to the energy radiated by ten thousand galaxies over the age of the universe.

The dilemma faced by current theories has caused some consternation, particularly because the gravitational models have appealing features from the standpoint of high energy particle physics. It is clear that the continuing and widespread interest in cosmology and its implications for the large scale structure of the universe will motivate many programs in observational astronomy during the next several years. Further work is required to determine just how empty the voids really are, and it is also necessary to search for any gaseous intergalactic matter in the voids. How common is the large scale streaming motion? Additional and more distant surveys need to be carried out, and one is currently being planned at KPNO, using rich Abell clusters of galaxies. The possibility of using another velocity independent distance indicator in the infrared is also being explored. A crucial element in cosmological models is the evolution of structure with time, and because galaxies are too faint to be detected at the relevant look back times, surveys of quasar distributions are of great importance. Some programs have been started in this area, and more are planned in the future. In all of these programs, the new telescopes and instruments planned for use at NOAO will be essential to their success. For example, the large collecting area of an 8-m telescope, when coupled with the speed of a fiber-fed multi-object spectrograph, results in an improvement of nearly two orders of magnitude over current facilities. This will allow the study of faint quasars and clusters of galaxies at redshifts between one and two, which is an essential period in the study of the evolution of large scale structure.

**B. The Formation and Evolution of Galaxies**

The simplest view of galaxy formation and evolution would entail some early epoch when galaxies formed together with their constituent stars, with all subsequent evolutionary effects being the result of the relatively slow and continuous process of stellar aging. Until quite recently this view was the prevalent one. Observations taken over the past several years, particularly at KPNO and CTIO, have shown the need to modify this view, but not to abandon it altogether. It is important to note that many of these observations simply could not have been made without the current generation of sophisticated solid state detectors and their accompanying instrumentation.

One of the first indications of a more complex picture was obtained several years ago when H. Butcher (Kapteyn Obs.) and G. Oemler (Yale U.), using the KPNO telescopes, discovered that rich clusters of galaxies appear bluer as their distance increases. Nearby rich clusters tend to be populated with old, quiescent elliptical galaxies, yet these observations suggested that at earlier epochs such galaxies were undergoing significant amounts of star formation. The clusters surveyed extended out to a redshift of approximately 0.4, which corresponds to looking back
approximately one-quarter of the age of the universe. This result, which has since been confirmed, indicates a much more significant evolution of elliptical galaxies in clusters than had been previously thought. A second set of relevant observations comes from a survey of the galaxies associated with strong radio sources. H. Spinrad (U. of California, Berkeley) and S. Djorgovski (Ctr. for Astrophysics), using the KPNO telescopes, have obtained data on some of the most distant galaxies observed. Looking back to times half the age of the universe or earlier, they find that these radio galaxies contain a great deal of hot, ionized gas which is in very rapid, turbulent motion. The galaxies themselves often appear distorted or moderately disrupted. By way of contrast, similar strong radio sources nearby are found to be associated with old elliptical galaxies which contain very little gas and which are regular and undisturbed in appearance. Hence there is strong evidence for major changes with time for this special class of galaxy.

Further evidence for evolution was found by A. Tyson (Bell Labs.) in examining the environment of quasars at two different epochs. The CTIO and KPNO telescopes were used to observe quasars in the redshift ranges 0.1 - 0.5 and 1.0 - 1.5. Tyson found that the more distant quasars had ten times more galaxies around them than did the nearby sample, indicating a drastic decrease in luminosity for these galaxies with time. Another unbiased sample was obtained by Tyson and P. Seitzer (Space Telescope Science Inst.) with deep CCD imaging. This survey found that galaxies at half the age of the universe are consistently more blue and thus have much more active star formation than at the current epoch. Perhaps the most striking case has been the recent discovery of a very large (100 kpc) cloud of ionized gas at a redshift of 1.82, which looks back to two-thirds the age of the universe. No stellar population is found, though a radio source is present. The data are consistent with this being a galaxy in the process of formation. A final complication emerges from the work of D. Hamilton (California Inst. of Technology) at CTIO, which shows there to be a very old, unevolving population of red galaxies which have basically been unchanged for about half the age of the universe.

Thus, recent observations show that galaxy formation was far from coeval, that galaxies may have been forming throughout the age of the universe, and that many, but not all, have undergone dramatic evolutionary changes in that time. The possible nature of these evolutionary forces is also becoming more clear through recent work at NOAO and elsewhere. In many cases, those galaxies which show strong evidence for evolution are found to be in special circumstances, i.e., in clusters of galaxies, near quasi-stellar objects, or associated with strong radio sources. Membership in a cluster of galaxies provides several mechanisms which can perturb a galaxy and thus change the history of its star formation. Near encounters with other galaxies, stripping of gas by ram pressure of the intergalactic medium, or conversely accretion of such gas by cooling flows onto a massive central galaxy are all possibilities. It is by no means clear which of these processes is relevant, and much further work needs to be done. That the proximity of quasars to galaxies may be important was implied by Tyson's survey. In addition R. Green (KPNO) and H. Yee (U. de Montreal) have used the facilities at NOAO and the Canada-France-Hawaii Telescope to show that the clusters of galaxies associated with quasars become much richer beyond a redshift of about 0.5. The exact nature of this interaction is again unclear, but the reality of the effect is not. T. Heckman (U. of Maryland) and his collaborators have used NOAO telescopes to determine that galaxies associated with radio sources often reside in regions of higher galaxy density than do similar galaxies which are "radio quiet." In addition Heckman, G. Miley (Space Telescope Science Inst.), W. van Breugel (U. of California, Berkeley), and their collaborators have, in a multi-year program, established that many radio galaxies have copious amounts of hot ionized gas, enriched with heavy
elements and spread throughout and beyond the galaxy. Such galaxies often show a
distorted morphology. This body of data again indirectly suggests the presence of
some form of interaction among galaxies.

Thus it may be that encounters with other galaxies are a condition for rapid and
dramatic evolution of galaxies. However, the deep CCD survey of Tyson and
Seitzer implies that many isolated galaxies have also undergone significant evolution.
Even more persuasive evidence for the evolution of isolated, field galaxies comes
from the extensive work done at KPNO by D. Koo (U. of California, Santa Cruz), R.
Kron (U. of Chicago) and their collaborators. Because redshifts of very faint,
distant galaxies are difficult to obtain in large numbers, these investigators have
used a measurement of the colors of galaxies in several passbands to estimate their
distance. Examination of about 10,000 field galaxies by this method indicates that
more distant isolated galaxies are also more blue than those nearby, and this is
indicative of more active star formation in the past.

A particularly elusive indication of galaxy formation and evolution comes from the
"forest" of Lyman alpha absorption lines seen against distant quasars. These
systems have been observed at NOAO by D. York (U. of Chicago) and by Green and
J. Bechtold (Carnegie Inst.), but their exact nature remains in doubt. A possibility
is that these systems are produced by galaxies or protogalaxies lying along the line
of sight to the quasar, but a better definition of their properties is needed to allow
resolution of this question. Another group of galaxies which may be undergoing
dramatic evolution are those recently detected by the Infrared Astronomy Satellite
(IRAS). These objects emit up to ten times the luminosity of a normal spiral
galaxy, with the emission mostly in the far infrared region. The presence of
copious amounts of dust is suspected, but many more observations will be required
to define these objects properly.

Although a wealth of data apparently exists concerning galaxy formation and
evolution, much of it is very new and rather sparse. The questions are just now
emerging, and much more data must be gathered before the relevant issues can be
well defined. What is the role of the environment of galaxies upon their
evolution? What are the important aspects of galaxy interactions: near, distant,
gaseous, and gravitational? If the implications from current data are true, what
causes some galaxies to delay their formation and others not to do so? Is there a
single cause of galaxy formation? Why do some galaxies become radio sources and
others not? The answers to these and related questions will clearly involve many
large scale observing programs which will require significant use of present and
planned NOAO facilities. A resolution of the problems posed will depend on the use
of large and complete statistical data bases. Fiber-fed spectrographs on medium and
large aperture telescopes, two dimensional infrared arrays, large format optical
detectors, and enhanced state of the art computing facilities will all be essential to
these programs during the period of this plan.

C. Star Formation

In view of their proximity, and the number of years devoted to their study,
surprisingly little is known about how stars form. Processes involving the
formation and evolution of the parent clouds, their fragmentation and collapse, the
role of angular momentum and magnetic fields, the establishment of the initial mass
function, and the evolution of protostars and very young stars are all areas of
active investigation. NOAO facilities have been used to observe regions of star
formation in our own and in nearby galaxies, and the advent of two dimensional
detector arrays that operate in the infrared will stimulate the growth of even more observing programs relevant to this topic.

It has become well established that the collapse of protostellar clouds to form new stars is accompanied by an outflow of mass from the central region, and several programs have used NOAO observations to investigate the nature of these outflows and their implications for the star formation process. These outflows are usually anisotropic, often bipolar, and sometimes very highly collimated. An important question, which has been examined by several groups, is the origin of this outflow and the mechanism for its collimation. In some cases the outflow is seen to be collimated to within 100 AU of the surface of the young stellar object, but it is still unclear if the wind is intrinsically bipolar or if it is collimated by material around the star. Some evidence for a circumstellar disk has been obtained by S. Strom (U. of Massachusetts) and his collaborators, which argues for an external collimation mechanism. However, additional data are needed. A successful understanding of this very common outflow phenomenon would provide valuable information about the role of angular momentum in the star formation process, about the efficiency of stellar collapse and the role of circumstellar material, and about the conditions at the surface of the young star itself.

Another phenomenon related to the star formation process is the Herbig-Haro objects, which are emission line nebulae thought to originate from the interaction of matter ejected from a young star and the interstellar medium. Observations are consistent with highly supersonic outflow, often accompanied by a larger scale less rapid outflow in the parent molecular cloud. It is not clear if the rapid outflow is continuous or intermittent, nor is the mechanism known that produces the high degree of collimation that is observed. Understanding of this would shed light on the nature of both the young stellar object and its environment.

A crucial factor in any consideration of star formation is the initial mass function, which describes the number of stars formed as a function of their mass. A knowledge of this function is essential for our understanding of the evolution of our Galaxy and other galaxies; a knowledge of how this function acquires its form would impart most of the information needed to understand the star formation process itself. Although work on this problem has proceeded for several decades, recent observations are beginning to reveal fundamental aspects of the mass function. An example is recent work on the mass function for stars more massive than about 20 solar masses. Until recently, little was known about the form of the mass function in this region, but work by C. Garmany and P. Conti (U. of Colorado) and C. Chiosi (U. di Padova, Italy) and by R. Humphreys and D. McElroy (U. of Minnesota), all using NOAO facilities, has clarified the mass function for these stars in our Galaxy. In addition, Garmany et al find evidence for a variation of the mass function with galactocentric distance, while Humphreys and McElroy do not. A resolution of this issue is very important, since global variation of the mass function could imply that star formation is not a purely local phenomenon but instead may depend on the structure of the galaxy as a whole.

Another essential feature of our understanding of star formation is a knowledge of how it may differ in galaxies other than our own. The nearest galaxies are the Magellanic Clouds, visible in the Southern hemisphere, and the unique facilities at CTIO have been used for studies of star formation in these objects. For example, H. Butcher (Kapteyn Obs.) found some time ago that the luminosity function in the Large Magellanic Cloud (LMC) was similar to that in the neighborhood of the Sun, but that star formation in this small irregular Galaxy may have begun more recently than in our Galaxy. L. Stryker (Arizona State U.) also found a young stellar
population in this Galaxy, which resided in the gas poor halo regions. R. Humphreys (U. of Minnesota) and her collaborators have made several studies of the Magellanic Clouds and find significant differences in the luminous stellar populations of the very metal poor Small Cloud, and the Large Cloud, but less difference between the Large Cloud and our Galaxy.

Evidence that global properties of a galaxy alter the local star formation process has also been found by P. Massey (KPNO) and his collaborators in studying massive stars in the nearby galaxies M31 and M33. Such stars in our Galaxy lose mass through rapidly outflowing winds originating at their surface. Massey et al find that the winds from similar stars in these galaxies are much slower than those in our Galaxy, and this striking difference in stellar evolution can be attributed to the different overall metallicities of the different galaxies. J. Gallagher and D. Hunter (Lowell Obs.), and their collaborators have also made extensive studies of star formation among different galactic types. In comparing irregular and spiral galaxies, they find that irregular galaxies have a nearly constant star formation rate, with a mass function similar to that of our Galaxy. Other spiral galaxies however, appear to have undergone a global burst of star formation in their past, in addition to a constant recent star formation rate. What emerges from these varied observations is that the global structure and evolution of galaxies has a dramatic effect on star formation and evolution.

It is clear that many productive areas of investigation are emerging in considering star formation, both in the local phenomena of protostars, mass outflow, circumstellar shells, and accretion disks and in the global aspects such as the initial mass function and the variation of star formation with changes in metallicity, turbulence, and magnetic fields. A major impetus for new and continuing programs in star formation will come from the availability of two dimensional infrared array detectors. Each element of these 62 x 58 InSb arrays will outperform any single detector presently used in infrared astronomy. For the first time it will be possible to study in detail the star forming regions in other galaxies such as the Magellanic Clouds and members of the local group. In the Galaxy itself, the problem of low mass star formation and the lower mass region of the initial mass function can now be addressed. It will be possible to identify and study stars below the critical mass for nuclear ignition and to examine accretion disks around protostars and young stellar objects. The arrays will also make possible the search for particle disks around main sequence stars, these being the presumed progenitors of planetary systems.

D. Stellar Structure and Evolution

Pursuit of questions concerning stellar structure and evolution not only reveals how stars evolve but also sheds light on such diverse topics as star formation, the chemical and dynamical evolution of the Galaxy, the calibration of the distance scale, and the age of the universe. For example, J. Stauffer (Smithsonian Astrophysical Obs.) has obtained rotational velocities for stars in the Pleiades cluster, and he finds that nearly half of the stars observed have rotational velocities much higher than expected. This indicates that a major portion of the angular momentum of the protostellar cloud is retained during collapse and is not shed into a circumstellar disk. Stellar spectroscopy is raising questions about the dynamics of star formation in the Galaxy. J. Hesser (Dominion Astrophysical Obs.), W. Harris (McMaster U.), and R. Bell (U. of Maryland) have found variations in the chemical composition of main sequence stars in the globular cluster 47 Tucanae. Stars in such clusters are thought to have formed at the same epoch, hence these results raise questions about either the chemical homogeneity of the gas cloud that
formed the cluster or about mixing within the stellar interiors. Much further work is needed in determining the compositions of stars in globular clusters. The chemical composition of another class of stars, M giants in the galactic bulge, has been studied at CTIO by J. Frogel (KPNO) and A. Whitford (Lick Obs.) who find them to be extremely metal rich and unlike stars near the Sun. Remarkably, these M giants are very similar to the major constituent stars in giant elliptical and S0 spiral galaxies. This provides an opportunity to study close at hand a stellar population similar to that of the largest galaxies in the universe.

Spectroscopy of stars in our Galaxy is providing new and very interesting results that bear on the formation of the Galaxy, and by implication, on the formation of all spiral galaxies. D. Geisler (CTIO) has used NOAO telescopes to study star clusters in the galactic disk in the direction of the anticenter. He finds a population of metal poor stars which are younger than those found in other parts of the disk, and this important result implies that the entire galactic disk was not formed at the same time but rather that the outer portions formed much later. A complementary result has been obtained very recently by K. Gilroy (U. of Texas), C. Sneden (U. of Texas), C. Pilachowski (KPNO), and J. Cowan (U. of Oklahoma) in their study of r and s process elements in halo stars. By coupling their results with known nucleosynthetic processes in stars of differing mass, they have been able to determine that the extreme halo population of stars in the Galaxy was formed in a very short time--about 10 million years. These two results have profound implications for models of galaxy formation, and they will provide motivation for additional observational and theoretical programs in the future.

The above examples illustrate the broad range of stellar programs being carried out with NOAO facilities. Many of these are just now becoming well defined and will require further observations. In most cases, the next step is spectroscopy: of more stars, intrinsically fainter stars, more distant stars. Among young star clusters, more work must be done to understand the relation between star formation, stellar activity, and magnetic fields. Much work remains to be done in the area of stellar evolution through the study of the surface compositions of stars at different phases of evolution and to understand the role of mixing. Scientific programs in the area of spectroscopy of stars in clusters will benefit especially from multi-object capability, which will allow observations of many individual stars in a cluster simultaneously, and NOAO is active on several fronts to bring about multi-object capability on the telescopes. Another facility which will dramatically affect stellar astronomy is the proposed distributed optical array telescope. For example, we anticipate that this high resolution instrument will allow the imaging of stellar atmospheres to allow a determination of their structure, to test ideas of how stars lose mass in the form of gas and dust, and to provide a detailed picture of the central regions of protostars where the collapse processes are the most complex.

E. The Sun

A study of the nearest star continues to yield new results about its structure and evolution, but our understanding of the Sun is far from complete. Current research programs are investigating the internal dynamics of the Sun, the origin and evolution of its magnetic field, the structure of its atmosphere, and the nature of its variability. One of the most active areas of research is that of helioseismology, which uses acoustic waves to map the interior structure of the Sun. The objectives and program of the Global Oscillations Network Group are described in Chapter IV, but other programs in helioseismology are also being carried out at NOAO. Past and present efforts have revealed much about the internal rotational characteristics of the Sun. As angular momentum is lost via the
solar wind, questions arise as to the redistribution of rotational energy in the interior. Is the slowing confined to the convection zone, or is it uniform? How does the rotation rate vary with depth? A very important question has involved the effect of interior angular momentum on the perihelion of Mercury through the solar gravitational quadrupole moment. If the interior angular momentum is large, this effect could seriously alter one of the major tests of Einstein's theory of General Relativity. These questions have been answered in considerable degree by use of NOAO facilities. J. Harvey (NSO), T. Duvall (NASA), and their collaborators have observed intermediate degree p-mode waves to infer that the equatorial rotation over much of the interior is very similar to that at the surface, with the possible existence of a relic rapidly rotating core. The internal angular momentum is such that the derived quadrupole moment is consistent with Einstein's General Relativity Theory. Other seismology measurements using NOAO facilities and instruments have examined the structure of the convection zone, especially in search of the giant convective cells, confirmed the value of the solar oblateness, and discovered a temperature anomaly below the convection zone.

Magnetic fields control solar activity, and NOAO has sustained an active and long term research effort in this area. Synoptic observations have defined the properties of small scale eruptions of magnetic flux, which apparently originate at the bottom of supergranules and which contribute a significant fraction of the overall solar magnetic flux. These observations, when converted to motion picture form, show that most flux disappears near its eruption site except for some poleward diffusion. The reasons for this behavior are unclear. The magnetic structure of the chromosphere, in particular the very strong magnetic fields around active regions, is beginning to emerge from infrared observations of Zeeman splitting in emission lines in this region. Polarimetry has also shown that the apparent downward flow in flux tubes is caused instead by gradients in non-steady mass outflow. Solution of the long standing problem of coronal heating requires extremely high resolution observations of magnetic structure, and progress is being made in this area, principally through the development of adaptive optics. Observations over short intervals with a resolution of 0.3 arcsec have already been made.

Solar research in the forthcoming years will be an area of great activity. In addition to the new initiatives in solar astronomy described elsewhere, technical advances are coming to fruition which will allow progress to be made in many areas. Solar interferometric imaging is being developed at NOAO, and in the future one can expect to obtain extremely high resolution images of the Sun in a routine manner. This will enable a detailed study of the fine scale, rapidly changing features on the solar surface as a function of wavelength. Such data provide access to many important physical processes: magnetic field emergence, the formation and decay of active regions, wave propagation, and the initiation of solar flares. Enhanced capability at infrared wavelengths resulting from new detectors will allow an improved understanding of the coolest part of the solar atmosphere via use of the rotation-vibration bands of the CO molecule as a thermometer. Improved infrared observations will also permit an accurate definition of the magnetic and dynamic state of the upper photosphere and lower chromosphere. Measurement of Zeeman splitting, which increases with the square of the wavelength, is especially important in this region because it is here that the dynamics begin to be controlled by magnetic effects and the importance of radiation and hydrodynamics recedes. Helioseismology will not only benefit from GONG, but additional effort will be made to observe the higher degree modes inaccessible to the network. These modes are best suited for sampling the flows in the convection zone, and their observation will provide essential information about the dynamics of solar convection.
F. Scientific Staff

The quality of the scientific staff is the primary determinant of the quality of NOAO's programs. It is the scientific staff that must bear the responsibility for identifying major opportunities in astrophysical research and for designing facilities and instrumentation; these in turn will allow NOAO's community of users to push back the frontiers of knowledge of the origin and evolution of the universe. In addition to defining the future course of NOAO, the scientific staff also plays a critical role in current operations. They are closely involved with overseeing the implementation of the instrumentation program, with evaluating and maintaining the performance of existing facilities and instrumentation, and with providing the link between NOAO and the users of its observatories which guarantees that NOAO's programs match the needs of the astronomical community.

Despite the critical importance of the scientific staff, budgetary constraints have forced a decline in the number of scientists and in the support for their research programs at CTIO, KPNO, and NSO. Table III shows recent trends in scientific staffing levels. The tabulated FTEs include all NSF supported scientific staff—tenured, tenure track, support scientists, and postdocs.

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<td>24.3</td>
<td>21.5</td>
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<td>13.3</td>
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<td>12.0</td>
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<tr>
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<td>13.5</td>
<td>13.0</td>
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<td>TOTAL</td>
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<td>64.2</td>
<td>59.8</td>
<td>58.3</td>
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As the table shows the total number of scientific staff overall has held rather constant since FY 1984, but staff has decreased at some individual sites. The greatest percentage decline in scientific staff has occurred at KPNO, where the number of scientists supported by NSF funds decreased by 23 percent between FY 1984 and the beginning of FY 1988. Staff reductions have occurred at all levels. Departing tenured staff have not been replaced, and the number of support scientists has been cut by a factor of two. The remaining staff is struggling to meet the diverse service responsibilities for the instrumentation program, supporting visitors to the mountain, and developing proposals for major new telescopes.
Not only has the NSO staffing level been reduced by 14 percent, there has been a shift in positions from Sacramento Peak to Tucson. The Sacramento Peak scientific staff has declined by more than a factor of two over the past five years, and the four NOAO staff, including one postdoc, that remain clearly cannot provide adequate on-site support for the premier solar observatory in this country. One position will be transferred from Tucson to Sacramento Peak even though this position has been supporting the nighttime synoptic program at the McMath, another very high priority program for NSO, which will thereby be significantly weakened.

At CTIO the size of the scientific staff has declined by four between FY 1985 and the beginning of FY 1988, with only 12 scientists remaining. Again, CTIO feels very strongly that additional scientific staff must be added if that observatory is to continue to provide state of the art instrumentation to the community. Only ADP, a new program, has seen an increase in scientific staff. Two soft money positions are also available to ADP.

The users' committees and all of the Associate Directors of NOAO have recommended that the size of the scientific staff be increased, but level of effort funding will not allow us to do so. With an increase in the budget we would propose to add two scientific staff at each site. We would also implement the recommendations of a variety of advisory committees that we offer graduate student internships for students working on Ph.D. dissertations. In addition, we would like to create a form of extended staff whereby we invite visitors for long periods of time to develop specialized instrumentation or to provide critical leadership for other major NOAO programs.

The observatories within NOAO have long supported a program of postdoctoral positions. Many of the nation's most outstanding astronomers have been a part of this program. It, too, was a victim of recent budgetary constraints. No new appointments in the postdoctoral category were made during 1986. Very high priority was placed on restoring this program, and accordingly six new appointments were made during the spring of 1987. Each division now has at least one postdoc on its staff. The long-term goal is to make one new appointment in each division, and the budget reflects that.
III. INITIATIVES

Throughout much of this long range plan, stress is placed on the importance and the scientific impact of investments in instrumentation for the telescopes at Kitt Peak, Sacramento Peak, and Cerro Tololo. Investments in new technology such as adaptive optics and interferometry will, over a somewhat longer period of time, also reap major scientific rewards when installed on telescopes already in operation. However, simply upgrading existing facilities is not enough if U.S. astronomy is to continue to play a leadership role in astrophysical research on an international level. Plans are already formulated and funding seems assured for a major initiative in telescope construction by Japan. The European VLT has already been approved with total funding of approximately $240M.

In this chapter, five initiatives are outlined that are essential to ensure the continued vigor of the community served by NOAO. Two key projects require substantial capital investment. The first is a program for building large optical/infrared telescopes, beginning with the construction of two or more 8-m telescopes during the time interval covered by this plan. The second would provide a new facility for high resolution studies of the Sun.

In addition, two other lower cost initiatives are needed to provide important enhancements to observing opportunities. One would lead to the construction and operation of additional 4-m facilities; the other would provide for synoptic observations of stars with the goal of achieving a better understanding of the physical mechanisms that control both solar and stellar activity. The fifth initiative would have as its goal the construction of a prototype test facility that would permit the exploration of techniques for optical and infrared interferometry. With a concerted effort to develop the necessary technology, it will be possible to achieve spatial resolution in these wavelength regimes that has previously been matched only by radio interferometers. Separate proposals will be developed for these initiatives, but a brief summary of the scientific goals of each project follows.

These initiatives have been chosen after careful consideration of timing and funding requirements. NOAO’s pursuit of these initiatives reflects our assessment of their scientific merits and importance to the nation’s astronomy effort; the time sequence for implementation of these projects is consistent with the pace of technology development and has been chosen to limit the number of concurrent activities. The 4-m telescopes would be nearing completion at about the time that construction of 8-m telescopes could begin. The commitment to a new solar facility would follow additional development of adaptive optics. Work on interferometric techniques would continue throughout the period covered by this plan. Support for construction of the 4-m and synoptic telescopes would be sought through collaborative efforts with universities. Proposals will be submitted to the NSF for construction of two 8-m telescopes, for which some private funding will be sought as well; for a portion of the new facility for solar astronomy, which will be a collaborative effort involving many groups; and for the exploration of interferometric techniques. We have not prioritized these initiatives since each is critical to its subdiscipline in astronomy.

A. Large Telescopes

For the first time since the completion of the 200-inch Hale telescope in 1948, it is technically feasible to build telescopes with significantly larger apertures. This alone would represent a major step forward for astronomy, but these new
telescopes will be more than simply larger. By taking advantage of new technology for adaptive optics, interferometry, large format CCDs, infrared arrays, and high throughput, stable, multi-object spectrographs, it is possible to build facilities that will support qualitatively new kinds of science.

In response to this opportunity, several groups both in the U.S. and abroad are planning to build telescopes with apertures in the range 8-m to 10-m (see Table I). NOAO plans a two-step program of construction of large telescopes. The first step is to build two or more 8-m telescopes, with at least one in each hemisphere. The construction of these facilities will be followed by the development of a 16-m equivalent aperture telescope.

Scientific justification.

Both the 8-m and 16-m projects and the scientific justification for them will be detailed in proposals that will be submitted to the NSF; the proposal for the 8-m telescopes will be submitted in early FY 1989. It is appropriate here to describe only briefly some of the scientific breakthroughs that can be achieved with the power of these telescopes.

The form of the present day large scale structure in the universe, and its evolution to that form, depend critically on physical processes in the early universe. In particular the evolution of large scale structure depends upon the thermodynamic properties of the material that constitutes the dark matter. Locally the largest structures are more than 100 Mpc across, and these structures are frothy so that galaxies populate the interstices between large voids. Redshift surveys to faint levels carried out with 8-m and 16-m telescopes will enable the structure to be investigated at a much earlier epoch, i.e. when the universe was between one-quarter and one-half its current age. In cold dark matter scenarios dense structures form late in the evolution of the universe so that we expect to see no rich clusters of galaxies at redshifts beyond z = 1, but 4-m surveys already suggest that such clusters may exist. The angular scales and large numbers of galaxies at faint magnitudes suggest that it is unlikely that complete redshift surveys will be carried out at high redshifts over the angular scales that correspond with those seen in the local universe. However, pencil beam redshift surveys carried out with large telescopes will indicate the distribution of voids along the line of sight.

A second fundamental question concerns the extent to which luminous material traces the distribution of matter. Is there a significant amount of mass outside individual galaxies or clusters of galaxies? In order to analyze the dynamics of galaxies and galaxy clusters, we will require thousands of spectra. With multiple object spectrometers, 8-m telescopes can provide a solution to this formidable but essential question.

Quasar absorption lines are another tracer of the intergalactic medium and can be used to probe the haloes of galaxies at a very early epoch. Extremely high resolution and high signal-to-noise spectra are required because of the complex velocity structure of individual lines. With a 4-m telescope it requires about two nights to obtain the desired signal-to-noise ratio at 5 km/s resolution for the brightest quasars in the sky with a redshift of z = 2. With a 16-m telescope we can observe more than 50 quasars with redshifts greater than z = 3 with the same accuracy and, because of the very steep quasar count slope, can observe 50 times as
many quasars with redshifts in the range $2 < z < 3$ as are accessible to a 4-m telescope.

There is increasing evidence that galaxy evolution can be detected even over fairly recent timescales. Observations indicate that there is evolution in color, luminosity, and the nature of nuclear activity for $z > 0.5$. The effects at $z = 1$ should be nearly double or triple those seen at $z = 0.5$, and so obviously it is important to extend measurements to as large a redshift as possible. The observational problem is that galaxies reach their minimum angular diameter at $z = 1$, and surface brightness declines in proportion to $(1 + z)^3$. To determine changes in stellar population, kinematics, and star formation rate as a function of time for $z$ as large as one requires the power of 8-m telescopes.

Its capability for interferometry over a 21-m baseline makes the 16-m NNTT, with four 8-m mirrors on a single mount, a uniquely powerful instrument. Star formation is an area of research where major advances become possible with the spatial resolution offered by the NNTT. The condensation of a star from the interstellar gas is the end result of poorly understood processes that amplify the gas density by a remarkable factor of approximately $10^{24}$. The majority of the power radiated by a gravitationally contracting protostar is reprocessed by its circumstellar dust and emitted at infrared wavelengths greater than about 5 $\mu$m. A low mass system with an effective temperature of 50 K and a bolometric luminosity of 100 L$_{\odot}$ will have a radius of only about $3 \times 10^{-3}$ pc. At a distance of 1 kpc, typical for galactic star forming regions, this size corresponds to an angular scale of 0.8 arcsec. With its long baseline and infrared beam combiner, the NNTT offers the opportunity to resolve individual protostars in their "cocoon" phase, and thus to probe their circumstellar environment. This high spatial resolution, coupled with high spectral resolution, will allow us to study the dust distribution and gas flows in the dust shell that surrounds the protostar, and hence to probe the conditions under which planetary systems form.

The interaction between a protostar and its surrounding gas is a dynamic process that has a major influence on the further development of the star and the larger gas cloud complex. Shocks are likely to form as high velocity gas from the protostar collides with cloud material. These shocks excite thermal emission from molecular hydrogen in the 2 $\mu$m region of the spectrum, and $\text{H}_2$ then becomes a fine probe of protostellar dynamics. Long slit spectroscopy of $\text{H}_2$ line profiles can be used to determine excitation temperatures and study the dynamics of the clouds, but measurements, particularly of the cooler regions, require the sensitivity of an 8-m telescope. The NNTT will make it possible to use the $\text{H}_2$ emission as a measure of star formation rates in other normal galaxies.

These new large telescopes will revolutionize the field of stellar physics by allowing us to extend to stars the kinds of observations that are now possible only for the Sun. Radial velocity seismology of solar-like stars is a valuable probe of stellar structure and convection. Seismology of stars as faint as magnitude 7.0 will be feasible with 8-m telescopes, and it will be possible to reach solar-type main sequence stars in the Hyades with the NNTT.

Speckle interferometry with the an 8-m telescope will resolve surface structure on a half dozen K and M giants and the NNTT would increase this number to 26. Measurements of their diameters and limb darkening profiles as functions of wavelength can test theories of stellar evolution and atmospheres. In principle, large convective patterns and their differential rotation could be detected as
temperature or Doppler shift patterns as in the case of the Sun. Speckle interferometry can also be used to determine the excitation temperature of the gas and the kinetic temperature of the dust in circumstellar envelopes around stars that are losing mass, and so to constrain physical models of mass loss.

Technical issues.

The goal of a nationally accessible 16-m aperture optical and infrared telescope was originally defined by the Astronomy Survey Committee (the so-called "Field Committee" report, Astronomy and Astrophysics for the 1980s, Vol. 1, pp. 15-16). Since that recommendation was made, several developments have led NOAO to the conclusion that it is desirable to construct 8-m telescopes as a logical step toward the 16-m facility. First, extensive site surveys, interferometric measurements, and other data from Mauna Kea suggest that the median full width half maximum image size is 0.4 arcsec, with 0.25 arcsec occurring about 10 percent of the time. No optical telescope now in operation can match the seeing on Mauna Kea. The construction of 8-m mirrors that can take advantage of this image quality is a major technical challenge.

The detailed measurements of seeing on Mauna Kea suggest that the average image diameter is about half the median actually observed at the telescopes already on the site. In order to realize the advantages of Mauna Kea, and of other sites as well, it is necessary to understand and correct the features of dome and telescope design that cause a degradation in image quality. If it is indeed possible to realize the full advantages of a site of the caliber of Mauna Kea, then much of the science originally planned for the 16-m can be carried out with an 8-m telescope. It is equally true that a 16-m telescope would be even more powerful than originally imagined.

There is also a clear scientific requirement that NOAO expand its observing facilities in Chile. Certain astrophysically important objects, including most notably the Magellanic Clouds, are observable only from the Southern hemisphere. During the next decade, several space observatories will be launched that are certain to have a profound impact on astronomy, among them the Hubble Space Telescope, AXAF, the Gamma Ray Observatory, and SIRTF. Experience with previous orbiting telescopes has shown that most of the important discoveries from space require ground-based follow-up study, and about one-third of the objects surveyed by these all sky satellites cannot be observed from Northern hemisphere observatories. Strong community interest in increasing U.S. optical capabilities in Chile is already evident, and several universities are considering locating 4-m telescopes on NOAO property in Chile. There is an additional private initiative to place an 8-m telescope on Las Campanas. NOAO believes that it is essential that there be a nationally accessible 8-m telescope as well.

Accordingly, NOAO in cooperation with the astronomical community will propose to the NSF to construct and operate 8-m telescopes in both the north and the south. These telescopes will be designed to take full advantage of the characteristics of the best available sites. We will work closely with the other groups that have undertaken the construction of 8-m telescopes on design studies and will examine the feasibility of co-locating our telescopes and theirs to minimize infrastructure and operating costs. The advantages of working with other groups in developing 8-m telescopes include better use of national and international talent and resources, cost savings, and time savings. Commonality of design where appropriate can save money for both the private groups and NOAO. Complementarity in telescope
performance specifications and in the selection of instrumentation can provide a much broader range of capabilities to the U.S. astronomical community as a whole than would be the case if these projects were uncoordinated. NOAO sees the construction of 8-m telescopes as a key step toward the development of 16-m and possibly even larger telescopes.

In order to implement this program, NOAO is preparing a plan which makes the scientific case for building 8-m telescopes and describes both the telescope design and the instruments to be provided. This proposal will be submitted to the NSF by early FY 1989. In developing the detailed scientific justification and technical specifications for the telescopes, we plan to call on the expertise in the entire community through workshops and other means. We have also begun to meet on a regular basis with working groups associated with both the Columbus (Ohio State, U. of Chicago, Italy, and U. of Arizona) and Magellan (Carnegie, Johns Hopkins, and U. of Arizona) projects.

NOAO's long range goal remains the building of the NNTT, an array of four 8-m telescopes, phased in the infrared, placed on a common altitude/azimuth mounting. Used individually, each telescope exceeds the power of any telescope in the world today. Used together, the four telescopes possess a light gathering power equal to that of a 16-m telescope and form a two-dimensional interferometric array with a 21-m baseline.

NOAO intends to equip the NNTT with adaptive optics so that the image size of 0.02 arcsec in the near infrared at 2.2 μm (the K-band) can be directly obtained. The NNTT, together with its powerful complement of instruments (optical and infrared spectrographs, optical and infrared imagers), will outperform all other existing and planned facilities. Its advantages lie in its large collecting area and sharp imaging, and in the outstanding quality of Mauna Kea—the site chosen for the NNTT.

The prime pacing technology item for the construction of both 8-m and 16-m telescopes is the production of finished 8-m diameter mirrors. The coalignment and cophasing system for the four NNTT telescope mirrors has been successfully prototyped. Development of a prototype adaptive optics system, which can be used at either an 8-m or 16-m telescope, is in progress. With the first 8-m mirror blank scheduled to become available in 1991, and with an estimated mirror polishing and figuring cycle of two years, we envisage an earliest date for a completed 8-m telescope to be 1994. The appropriate date for start of site preparation for an NNTT would be FY 1993, when the 8-m mirror would be complete and tested, and design studies and structural analysis of the NNTT will be carried out prior to that time.

A combination of advances in technology, in our knowledge of fundamental physics, and our understanding of astrophysics now allows us to attack basic questions about the origin and evolution of the material universe. One of the great strengths of U.S. astronomy is the diversity of sources of support. In no other country can astronomers mobilize both public and private support for astronomy in the way that we have. If universities and NOAO move aggressively to combine their talents and resources to ensure that major new telescopes are built, then the ensemble of facilities that result will ensure the continued pre-eminence of U.S. astronomy.
B. LEST

Scientific background.

The solar atmosphere is a superb astrophysical laboratory in which to study processes and interactions of fundamental physical importance in magnetized plasmas. The interaction of convection and magnetic fields in a compressible fluid; the generation, equilibrium, and decay of magnetic fields; the nature of electromagnetic and particle radiation from a magnetized plasma; and the mechanisms of energy transport are some examples. These processes are ultimately fundamental to our understanding of many astrophysical phenomena, including solar and stellar flares, the solar cycle, non-thermal heating of chromospheres and coronae, stellar mass loss, physics of accretion disks, and many more. Their detailed study is impossible in any object other than the Sun. Even there, the challenge facing solar physicists is that many of these processes take place at spatial scales below 1.0 arcsec. Ground-based solar telescopes rarely resolve structures smaller than 0.5 arcsec and then only for a few minutes, perhaps several times per year. An ad hoc committee chaired by R. MacQueen and reporting to the AURA Board reviewed the science that could emerge from a new generation of solar observations, taken at subarcsec resolution. It concluded that the science is potentially so valuable to astrophysics that NOAO should undertake to design a large aperture ground-based telescope that could exploit this research field.

NSO’s staff and visiting scientists are actively working in this field. For example, results have recently been published on the detailed spatial correspondence, at subarcsec resolution, of magnetic flux and photospheric convective cells. MHD waves have been observed that probe both the subsurface and upper layers of sunspots. The dynamic reaction of the solar atmosphere to the sudden release of magnetic energy has been investigated and indicates the appearance of powerful beams of electrons. The heating of the solar corona, the acceleration of the solar wind, the decay of magnetic flux during the 11-year solar cycle are all ripe subjects for a renewed attack, provided improved instrumentation becomes available.

Current instrumentation program.

NSO’s current program for high resolution studies of the Sun is aimed at improving and then utilizing the Vacuum Tower Telescope (VTT) at Sacramento Peak. During the next three to five years, a major effort will be made to optimize the VTT for vector magnetometry at subarcsec resolution. NSO and (High Altitude Observatory) HAO are collaborating in building a Stokes polarimeter for the VTT. A high-speed data collection and processing system (CHIRP) is being built at Sacramento Peak. Most important, NSO scientists are developing a segmented adaptive mirror system intended to correct image distortion instantaneously. With these improvements, the VTT can offer an excellent opportunity in the near term to investigate magnetic processes at relevant scales of resolution.

There are several limitations, however. The VTT has only a 75-cm aperture, resulting in limited photon flux (and signal-to-noise ratio) for spectropolarimetry and a theoretical diffraction limit of only 0.2 arcsec. The site, while among the best in use, may be surpassed by sites in the Canary Islands, Mauna Kea, or other locations. Although the VTT can continue to serve the U.S. community well, we anticipate that the full potential of subarcsec solar research will not be reached without a more advanced system in a better location.
The future.

One approach to achieving a more advanced system has been proposed by an international consortium formed over a decade ago to build a Large Earth-Based Solar Telescope (LEST). The consortium has accomplished two important goals: it has identified several sites where solar observing conditions are excellent and are currently comparing them; and it has designed, with NSO's help, a state-of-the-art vacuum telescope, patterned after the VTT at Sacramento Peak. The present design of the LEST has a 2.4-m objective, which will yield ten times the photon flux and one-third the diffraction limit of the Sacramento Peak VTT.

It appears probable at this time that the U.S. community's needs for subarcsec observations would best be met, from a technical standpoint, by participating as a full partner in the construction and operation of the LEST. No single nation has the resources (approximately $50M) to undertake such an enterprise for its relatively small solar and solar-stellar community, so that a cooperative venture makes economic sense. Some issues remain to be explored before committing fully to LEST, including the technical specifications for the telescope and its performance. The future of the proposed High Resolution Solar Observatory (HRSO) spacecraft, particularly if it becomes a free-flyer, will also strongly influence the planning for high resolution ground-based observations of the Sun. NOAO, in partnership with HAO, will continue to explore with the LEST Foundation the technical and management issues that are relevant to guaranteeing that LEST meets the needs of the U.S. solar physics community.

The development of an advanced adaptive optics system is an essential prerequisite for the technical success of the LEST. NSO plans to embark upon the development of an adaptive optics system which will permit spectrographic exposures of several seconds near the diffraction limit of a large telescope. Once a successful demonstration of such a system is possible and once a site worthy of a 2.4-m diffraction limited telescope has been identified, we would expect to propose full U.S. participation in the international LEST effort. A suitable path toward this goal would be for AURA to join with UCAR as co-equal partners in representing the U.S. in the LEST Foundation.

During the period of this plan, NOAO proposes:

- to continue to develop, test, and employ adaptive optics systems;
- to work with the LEST Foundation to define the technical specifications and funding requirements for the proposed facility, to negotiate for a corresponding fraction of the observing time for the NSO community of observers, and if these negotiations are successful to prepare a request for funding;
- to extend its current work in post-observational image reconstruction techniques and interferometric imaging;
- to continue to study alternative approaches toward high resolution observation.

All of these steps form an integrated approach to the development of a high resolution solar observing capability. In particular, a critical element of such a facility will be the demonstrated capability to acquire near diffraction limited...
images with adequate contrast on a regular basis. Such a demonstration should be a principal goal of initial funding and will pave the way for a commitment of substantial U.S. funding to the construction of a large solar telescope.

C. 4-m Projects

Scientific justification.

In addition to its program to develop 8-m and 16-m facilities for the astronomical community, NOAO recognizes a continuing need for additional 4-m class telescopes. It is likely that telescopes of this aperture will become the workhorses of the future that 1-m to 2-m telescopes are now. The challenge is to provide access to 4-m class telescopes within the National Observatories without slowing the momentum toward the construction of larger telescopes.

Both the Greenstein Committee and the Field Committee recommended adding new telescopes in the 2-m to 5-m class. Indeed the Field Committee assigned such telescopes as next in priority for ground-based initiatives after the NNTT. The NSF "Task Group for Coordination of Simultaneous Observations at the Hubble Space Telescope and the National Centers" has also recommended the construction of two new, nationally accessible, 4-m class telescopes, one in the Northern hemisphere and one in the South. Because there are fewer ground-based facilities in the Southern hemisphere, the NOAO Advisory Committee on Coordination of Space and Ground-Based Observing urged rapid completion of a 4-m telescope at CTIO.

The most pressing need, based both on existing requests for observing time and on our assessment of the scientific problems that can be addressed by 4-m class telescopes, is for a telescope that would be optimized for high and moderate resolution multiple object spectroscopy. This choice is driven by the significant gains to be made from observing many objects in a star cluster or cluster of galaxies, or many discrete points in an extended galaxy or nebula, simultaneously. The existing 4-m telescopes have been used to study selectively a small sample of objects of interesting classes; this approach is viable for some programs, but limits progress significantly for important astrophysical programs that require large scale spectroscopic surveys. The evolution of clusters of galaxies will not be understood until many clusters, not just a few, are systematically studied; such data are essential for the determination of the cosmological constant \( \Omega \). The large scale structure of the universe will not be known until hundreds of quasi-stellar objects, not just a handful, have been observed to map out the distribution of matter in the universe. The evolution of stars in clusters, and of stellar populations will not be well understood until large samples of stars can be surveyed. A new multiple object spectroscopic telescope can greatly expand our capability to obtain observations in such areas as QSO spectroscopy to study the large scale structure of the universe, studies of the evolution of clusters of galaxies, the study of stellar evolution through spectroscopy of stars in clusters, and the rapidly expanding field of stellar physics.

Specific examples of the types of programs that would benefit from multiple object spectroscopy include studies of the detailed element abundance changes with stellar evolution in stars in star clusters of different ages, studies of the binary frequency of stars in clusters of different ages and of different stellar populations, or the monitoring of activity in many stars along the main sequence of star clusters of different ages. Spectroscopy of many planetary nebulae in nearby galaxies out to 5 Mpc (such as the Sculptor group galaxies or M81) or of H II regions out to
10 to 15 Mpc will be possible. Observations of individual globular clusters in Virgo group galaxies to determine velocity dispersions and compositions can also be obtained efficiently using multiple object spectroscopy.

For the most recent six-month scheduling period, NOAO received over 200 observing proposals requesting almost 800 nights on its two 4-m telescopes. Proposals for telescope time at both the CTIO and the KPNO 4-m telescopes are dominated by requests for optical spectroscopic observations, particularly at moderate to high spectral resolution. A 4-m class telescope optimized specifically for optical spectroscopy will relieve much of the burden on the existing telescopes for these observations and will allow us to pursue survey and synoptic programs that cannot be accommodated with existing constraints on available observing time.

To confine our considerations to current scientific need is, however, insufficient; past experience teaches that space observatories in orbit, in preparation for launch, or in the planning stages will generate demands on ground-based facilities that we are ill-prepared to meet. Space observatories do not replace ground-based telescopes. Rather, they open up exciting new fields that can only be fully studied using large ground-based instruments. As an example, follow-up observations of x-ray sources discovered with the Einstein satellite have over the past few years accounted for almost one-quarter of the visitor use of the CTIO 4-m and 1.5-m telescopes. At KPNO, requests for observing programs to follow-up on IRAS observations continue to increase dramatically.

NOAO-university cooperation.

The clear requirement to move vigorously to meet the need of the astronomical community for access to 4-m class telescopes can be met by new approaches to funding and telescope construction. The technology being developed for very large telescopes is applicable to smaller ones as well, and along with advances in computer control, permits a significant lowering in the cost of construction. In actual dollars, the cost of building a 4-m telescope today is approximately equivalent to the cost of building the KPNO 4-m telescope. With allowance for inflation, this means that the real cost of construction is substantially lower and has come within the reach of many universities or university consortia.

While construction can often be financed by universities with relatively modest astronomy programs, only the largest groups are well equipped to assume the continuing burdens of operating and instrumenting telescopes. Telescopes of 4-m class aperture are complex and require substantial technical support for operation. Instrumentation, too, is becoming increasingly complex and costly to build.

We propose to meet the need for new 4-m class telescopes through partnerships between NOAO and university groups. Economies of scale can be achieved by concentrating telescopes at a few developed sites so as to minimize the cost of infrastructure support per telescope. There are already several telescopes on Kitt Peak that are not operated by NOAO, and they benefit from KPNO’s maintenance of roads, power lines, water systems, etc. and take advantage of our stock of spare parts, aluminizing facilities, and occasionally the specialized expertise provided by our engineering staff. Other groups will be encouraged to co-locate facilities at NOAO sites.

In some cases, it may be appropriate to extend cooperation beyond simply making sites available. Universities can raise funds from the private sector, and many of
them have extensive experience with capital fund campaigns. NOAO is experienced in operating facilities at a high standard of reliability and efficiency. One form of cooperation that would take advantage of these mutual strengths would be a partnership in which one or more universities provide the bulk of the construction costs for a telescope, while NOAO assumes most of the burden of operation. Observing time would be shared between NOAO and the universities according to their mutual financial contributions.

This approach has additional benefits in terms of planning and budgeting. While there would be a long term, but finite, commitment to operating costs, that commitment would represent a relatively modest increment in operating budgets (see Chapter V). The NSF would have a continuing role in monitoring the effectiveness of these facilities through its oversight of NOAO, and the NSF investment would provide access to these facilities to the entire community, not only to the members of a few universities.

At the present time NOAO has received four letters of intent from university administrations suggesting that we explore the feasibility of such partnerships for 4-m class telescopes. The basic principle could, however, be extended to other facilities, including 8-m telescopes, distributed arrays, or other projects consistent with NOAO's long term goals and budget. Criteria and a system of peer review for evaluating such proposals will have to be established, and discussions of how to do so are in progress within AURA.

A Northern hemisphere 3.5-m telescope. The letters that we have received from universities so far propose construction of one telescope in the Northern hemisphere and two in the Southern hemisphere. Because of the interest of the KPNO staff in a Northern hemisphere telescope dedicated almost exclusively to multiple object spectroscopy, planning is most advanced for that concept and will be described here. A Southern hemisphere 4-m, should NOAO become involved in such a project, might well be optimized for different scientific goals, but discussions between potential university partners and NOAO staff are at a very preliminary stage.

New 4-m class telescopes at NOAO in either hemisphere will be designed from the outset to provide capabilities not now available to us. They will have limited instrumentation; changes between available instruments will be designed to be rapid; and the capabilities will be complementary to the existing 4-m telescopes with minimum duplication of instruments. NOAO's share, which will be queue scheduled with staff doing most of the observing, will be used for surveys, synoptic programs, and projects that need simultaneous or near simultaneous observations at multiple wavelengths. With the high throughput offered by multiple object spectroscopy and with archiving of the data, we hope to provide the community with the same degree of access to 4-m observations that they now have to data obtained with 1-m telescopes.

Other advantages of building at least one 4-m class telescope are that NOAO can begin to develop the project group needed to construct 8-m and 16-m telescopes, gain experience with borosilicate mirrors, and explore the other technology that will be used with very large telescopes, including building instrumentation for alt-azimuth telescopes with rotating fields of view and developing approaches to flexible scheduling and remote observing.
As part of the technology development program in support of new technology large telescopes, NOAO will receive a 3.5-m, spin-cast, lightweight mirror from the University of Arizona. The mirror will be used to study the feasibility of fast, lightweight mirrors for large telescopes; the mirror will be polished to about f/1.5, and an active mirror support system will be developed to maintain the 0.25 arcsec images required by the best sites. The mirror, figured and with a support system, will be completed in late 1991. The development and construction of a new telescope facility would allow us to put this test mirror into a real telescope and to evaluate its optical performance under real astronomical conditions.

The scientific goals that we have defined for a 3.5-m telescope can be achieved with a simple Nasmyth design similar to the Astrophysical Research Consortium (ARC) telescope and consistent with the ARC mechanical design. The configuration we have chosen is a modified Ritchey-Chretien with dual Nasmyth foci and a thin Gascoigne type corrector. The primary focal ratio of the mirror is f/1.5, which will serve as a good test of mirror polishing and support techniques for the mirror technology development program. The effective focal ratio of the telescope will be f/5.

The images produced with our optical design are of excellent quality over the full one degree field of view (FOV), with 80 percent energy diameters of 0.2 arcsec at a distance of 30 arcmin from the optical axis (monochromatic at 5000 Å). Image quality on-axis is better than 0.1 arcsec. The image diameter is consistent with achieving seeing limited images under conditions of the best seeing to be expected at Kitt Peak. With the corrector removed from the beam, image quality remains good over the central field of 10 to 15 arcmin, but degrades rapidly for larger fields. The 10 arcmin diameter FOV corresponds to a physical dimension of 5.4 cm, roughly the size of a Tektronix CCD.

While NOAO will move ahead to provide multi-object capability on the existing 4-m telescopes, we can expect more optimized, and therefore superior performance from a new facility. The telescope will achieve gains in throughput and efficiency over the existing telescopes because of its optimally selected focal ratio, and its capability for quick instrument changes necessary to provide supporting observations for space experiments and synoptic programs.

NOAO prefers Kitt Peak as the site for a telescope that makes use of the borosilicate mirror for both technical and scientific reasons. From a technical standpoint, it is advantageous to have the telescope conveniently located for engineering tests in support of the mirror technology program. Scientifically, a Northern hemisphere site is preferred for stellar physics programs, since a history of observations of Northern hemisphere stars is already available. Technical and operational support facilities are already available at Kitt Peak, and the added costs of operation can be kept to a minimum. If a Southern 4-m class telescope is built at CTIO, it would make use of a mirror made of low expansion glass obtained from a commercial glass manufacturer. The scientific emphasis would probably be extragalactic astronomy rather than stellar physics.

D. SYNOP

Scientific rationale.

Synoptic programs comprise a fundamental aspect of the research on time dependent phenomena exhibited by the Sun on both short (e.g., flares to active region development) and long (e.g., solar cycle) time scales. High resolution
spectroscopy is a powerful tool through which the detailed physical properties and structure of the Sun can be ascertained. A key goal of solar physics is to apply these increasingly sophisticated diagnostic methods to the study of solar-type phenomena on other stars. Among the frontier areas of solar-stellar research that require high resolution spectroscopic, synoptic observations are the following:

• The interior structure and angular rotation distribution in stars may be deduced from the frequency spectrum of solar-like oscillations. Progress in this very young field of astroseismology requires precise radial velocity measurements of many spectral lines of solar-type stars during observing runs extending over at least one week with minimal interruptions. The observation of stellar oscillations is a natural and necessary extension of the GONG experiment.

• Systematic observations of nonradial pulsations in OB stars over many rotational phases are required in order to identify the physical family and properties of these modes. By so doing, we create an invaluable tool by which the interior structure of these hot stars can be probed.

• Convective motions in the photospheres of stars of various spectral types and luminosity classes can be inferred from asymmetries in spectral line profiles.

• Measurements of magnetic field strength and area coverage through the use of Fourier deconvolution techniques require both high spectral resolution (~ 100,000) and high signal-to-noise ratio (> 100). Systematic studies of the magnetic properties of stars as a function of spectral type, age, and rotational velocity should be extended to at least tenth visual magnitude. Furthermore, the magnetic properties of representative stars should be monitored over time scales ranging from hours to years.

• Doppler imaging is a relatively new technique for inferring the inhomogeneous distribution of dark spots or bright chromospheric active regions across the surface of a rapidly rotating star using sequences of spectra. This novel technique requires many spectra obtained over several rotational periods to separate long lived surface structures from transient events.

• Insights on the nature of explosive flare events, as they occur in thermal environments that are markedly different from that of the Sun, can be obtained by monitoring flaring in M dwarfs and other types of active stars. Time resolved spectra during flares are needed to infer the bulk fluid motions and energy budget of flares as a function of time.

• The further development of dynamo theory, that is, the understanding of the origins of magnetism in stars, requires sustained observations of appropriate samples of stars over a long time scale (~ 10 years). These kinds of observations are now crucially needed for stars that are fully convective, such as the M dwarf stars. It is vital to understand the nature of the dynamo in stars characterized by wholly convective interiors.

• Pre-main-sequence stars should be monitored spectroscopically on many time scales to infer temporal variations in the wind, surface structure, velocity fields, and magnetic field properties of these precursors to solar-like and early type dwarfs.
Despite the importance of these programs, the astronomical community faces severe difficulties in obtaining the required observations because (1) there are very few spectrographs equipped with modern detectors that have the characteristics of high throughput and high spectral resolution; (2) none of these instruments is available to the community as a whole with the important exception of the NSO McMath stellar spectrograph and CCD system; and (3) synoptic programs comprising monitoring and survey investigations place severe demands on the scheduling of telescope time that are inconsistent with the conventional mode of operation.

A workshop sponsored by the NSO was convened in Tucson during September 3 - 5, 1986, as a first step toward the establishment of appropriate observing facilities for synoptic stellar observations. The 28 workshop participants, who came from 15 institutions, adopted the acronym SYNOP (for SYNoptic Observing Program) to represent the conceptual and instrumental foundations of this initiative. The proceedings of the workshop were published by NOAO.

The SYNOP group adopted the following statements of needs and objectives:

- There is a vital need for a national facility dedicated to synoptic high resolution spectroscopy which will be open to the whole community.
- This facility should be built in partnership with NOAO.
- The facility will be a major impetus to the field of solar-stellar astronomy. However, observing time should be allocated to the highest quality programs to study stars or other relatively bright point sources regardless of the type of object to be investigated.
- The facility should be dedicated to synoptic high resolution programs selected by peer review. The observations for the various programs would be interwoven and scheduled on a queue basis. The data would be obtained by Resident Observers since the individual programs will typically require only partial nights of observing.
- The near term objective of the SYNOP program should be to design a spectrograph that can meet the needs of the stellar seismology community as these technical requirements are the most stringent.
- A clear need exists for a network of facilities distributed in longitude and latitude to permit very long observations of stars at all declinations. Such a network, which could consist of a variety of instruments, would facilitate coordinated and simultaneous ground-based and space observations.

The workshop established a Steering Committee, a Spectrograph Design Committee, and a Telescope Options Committee to guide the development of the SYNOP program within the context of the envisaged scientific goals, to design a spectrograph, and to examine the telescope options for the eventual placement of this innovative spectrograph as the key element of a new synoptic facility.

Spectrograph plans.

The near term objective of SYNOP is to design and build an advanced, visible light, fiber-fed spectrograph characterized by specifications that meet the observationally demanding requirements of astroseismology. R. Dunn (NSO) and
L. Ramsey (Pennsylvania State U.) are investigating design alternatives for the SYNOP spectrograph. The present design goal for the main spectrograph is to obtain simultaneously as large a portion as possible of the 4500 - 9000 Å range on a single 2048 x 2048 CCD chip at a spectral resolution of 100,000. Optional modes or separate smaller spectrographs will be available to observe the spectral region below 4100 Å at 30,000 resolution, and the full spectral range with lower resolution. The spectrograph will be fiber-fed so as to be adaptable to a variety of telescopes.

An option under consideration for the main spectrograph is a conventional cross dispersed echelle characterized by tangent (input angle) = 2. This spectrograph, known as the R2, has the virtues of simplicity, existing prototypes, availability of optical components (including the echelle grating), and the ability to obtain most of the required spectral range at one time with only two slices of the input beam and a 100 μm fiber. Some light losses would be incurred for a 2-m class telescope.

A second design under study is an innovative cross dispersed echelle spectrograph based on a tangent (input angle) = 4 echelle grating. This enables the beam and optical components to be smaller and thereby increase the throughput. If a large grating of this type can be ruled, then the "R4" spectrograph may be able to image most of the spectrum onto one chip with no image slicing and with acceptable light losses at the input.

Telescope options.

The Telescope Options Committee is examining telescope options in the 2-m to 2.5-m class. The most desirable option at this time is to design, fabricate, and install a new 2-m class telescope in the present #2-0.9-m building on Kitt Peak. This is an advantageous option since NOAO already owns a 2-m primary mirror blank. The telescope design would be based on the alt-azimuth telescope design concept described in a previous Kitt Peak study of the so-called Advanced Technology Telescope (ATT). The ATT design is a light weight, low cost configuration specifically intended to fit in the #2-0.9-m building. Furthermore, the design work has already been completed for the primary mirror support system.

A significant amount of work will be required in various areas of both the building structure and mechanical support equipment to accommodate the new telescope design. The primary mirror will have to be polished. The total cost for the design, fabrication, and installation of an ATT in the #2-0.9-m building on Kitt Peak is currently estimated to be about $1.6M. In order to run a synoptic program, at least two observers will have to be allocated to this facility for operations on a full-time basis. The other aspects of telescope support can be absorbed in the Kitt Peak mountain operations budget, since this new telescope would replace an older one that requires substantial maintenance.

Summary of a SYNOP scenario.

Support from the FY 1987 NOAO initiatives fund was allocated to SYNOP for the work of the SYNOP committees, including the spectrograph design studies. Following completion of the engineering design stage, a proposal for the construction of the SYNOP spectrograph combined with the option for a new 2-m class telescope on Kitt Peak will be formulated, reviewed internally, and submitted to the NSF in early FY 1989. The total budget for both the spectrograph and the telescope option is difficult to estimate in advance of an engineering design for the spectrograph. The entire SYNOP facility will take about three years to build following the initiation of funding.
E. Distributed Array

The need for a test array.

Many fundamental astronomical problems need much higher resolution than is afforded by atmospheric seeing or the diffraction limit of even the largest telescopes being planned. Studies of the structure of stellar atmospheres, the formation of stars, the mechanisms for mass loss in evolved stars, and the nature of the cores of active galaxies all require mapping at milliarcsec resolution. For example, the diameter of the largest star is 42 milliarcsec and a typical dwarf star like the Sun at a distance of 10 pc has a diameter of 1.0 milliarcsec. Light variability of the cores of active galaxies shows that substantial energy is radiated from structures with scales from tens of milliarcsec to fractions of a milliarcsec, the central source being unresolved. Although parameters such as angular diameter give important astrophysical information, it is the ability to produce reliable maps, often at different wavelengths, that is essential to obtain new insights into astrophysical processes.

The only way to achieve these resolutions is by a distributed array of telescopes similar to those used in radio astronomy. Before an optical VLA or VLBA can even be designed, we need to build a pilot array that will develop the appropriate technology. This facility could be used by universities for scientific observations or to test the design of new and better correlators and image formation techniques essential for the next generation of arrays.

NOAO intends to work with the community to develop a pilot imaging array of telescopes as a national facility. The array will work initially in the infrared. Simple thermodynamic arguments show that for a given central energy source, cooler objects tend to be more readily resolved with a given baseline. The peak emission of cool stars occurs in the near infrared and the continuum opacity is at a minimum at 1.6 μm. In the 2.0 μm band, we can usually detect the central star as well as the circumstellar envelope; the important molecular H₂ and CO bands allow exploration of the velocity structure of the brightest halos of both young and evolved stars. At 3.7 μm, we can explore cooler shells without extensive use of cooled optics in the array.

Telescope diameters of order 0.5-m give adequate sensitivity for most of the scientific projects discussed below and give a limiting magnitude of +9 at 2.2 μm for unresolved objects. The telescope structure can be made very stiff at this size and the aperture gives a phase coherent wavefront for wavelengths above 2.2 μm. In this sense, at 2.2 μm and above, the telescopes act more or less like radio telescope antennas. The operating wavelength can be extended to the visible, over the full aperture, by the use of adaptive optics (already under development at NOAO) or pupil division techniques (being developed at SAO). Such techniques will be developed as second stage improvements of the array and will allow the construction of larger telescopes, necessary to reach fainter limiting magnitudes.

Astronomy with the array.

Any direct imaging of stars to detect starspots and photospheric activity needs baselines of order 100-m. Stars such as α Orionis, ο Ceti, and R Leonis are expected to have considerable surface structure resolvable at such baselines. These objects are bright and can be observed with relatively high spectral resolution to provide detailed three-dimensional information about the atmospheric structure. In
the strong infrared CO line cores, such observations can be used to measure directly the geometric height of formation and the spatial structure of chromospheric emission.

The near IR is ideal for measuring the photospheric radius of pulsating Mira variables. Direct measurement of the time dependent behavior of the stellar radius enables the pulsation mode to be specified; with modest spectroscopic resolution it should be possible to follow the development and evolution of the shock waves in atomic hydrogen emission.

Long period variables, such as Miras, are thought to represent the intermediate class between giants and planetary nebulae. Some of these stars have remarkable rates of mass loss. An interferometric array will be able to yield well resolved multi-color infrared images of the important inner regions of the dust shell and, in particular, the shape of the inner envelope. Such observations are needed to determine how and where the dust is formed and accelerated away from the star. Many sources can be observed with the array. A typical source at $K = 0$ will have a stellar diameter of 10 milliarcsec and an inner dust shell diameter of 50 milliarcsec. Spectrally resolved spatial measurements in the strong lines of the gas shell contain potentially enormous amounts of information which can be correlated with VLBA radio and microwave observations.

Mass loss from hot stars can also be investigated. Many P Cygni and Wolf-Rayet stars brighter than $K = 7$ can be observed to map the shells in the various emission lines.

The array will be well suited to the detailed study of halos around young stars after the star has been formed but prior to complete disruption of the star forming environment. Very young stars are believed to eject material into the circumstellar region, often in the form of a bipolar flow. The flow is believed to be sometimes highly collimated and to contain clumps of material at enhanced density. Stars will be observable directly with the array; at 2.0 $\mu$m the starlight will penetrate the dust and can be used as a phase reference to produce good maps of these very young objects.

At the limit of sensitivity of the array with current detectors, several bright Seyfert galaxy cores should be observable. The source dimensions can be characterized and modest spectral resolution will suffice to distinguish the broad line H and H$_2$ emission regions from the infrared continuum regions.

Design of the array.

The number $M$ of telescopes needed in an imaging array is central to its design. Because we have no noiseless amplifiers at optical/IR wavelengths, the signal must be divided between $(M - 1)$ paths if we are to make use of all the baselines. The observing time to reach a given S/N increases as $(M - 1)$, as does the limiting flux for an unresolved object. However, an array of $M$ telescopes observes $[M(M - 1)/2]$ baselines simultaneously, so that for bright sources the time to cover the $(u, v)$ plane actually decreases by a factor of $M/2$. More telescopes permit faster observations. At optical/IR wavelengths there are, however, some additional constraints in determining the optimum number of telescopes.

- Closure techniques work by having all the baselines in operation simultaneously. If there are unacceptable phase errors across one or more telescopes at any instant these telescopes cannot be used and the advantage
of the full complement of telescopes within the array is lost. The more

telescopes in the array, the smaller the mean phase error must be across each
telescope and hence the smaller the collecting area per telescope. This

problem may be overcome using adaptive optics.

- The total losses introduced by beam division in the correlator increase with
  the number of telescopes. The loss is at a minimum for arrays of size $2^N + 1$
  (i.e., three, five or nine telescopes).

For detector-noise-limited operation, these conditions give an optimum number
of telescopes of five. Theoretical improvements are achieved for more telescopes
(for both background and photon noise) but the gain is not large. More important,
the dynamic range of the array is improved with more telescopes. Five appears to be
the minimum number required for a true imaging array. Thirty percent of the
amplitude information and 60 percent of the phase information will be measured,
independent of atmospheric conditions.

The NOAO strawman design of the array uses five 0.6-m alt-azimuth telescopes,
each movable along a radial track onto one of a number of locations. This
configuration gives good coverage of the $(u, v)$ plane, minimizes the length of delay
lines, and enables $32 \times 32$ pixel maps to be obtained for bright sources in five
hours' observation. Light from each telescope will be directed into a central
station via a 10-m delay line based on the design of the NOAO FTS. The cophased
outputs will be fed into a five element fiber optic correlator. Provision will be
made to switch all or any of the beams into a user port that will provide cophased
beams to feed correlators developed for other wavelengths and by other groups.

The array as a national facility.

The major costs of an interferometric array test facility are in the site
development, the telescopes, the delay lines, and the operational infrastructure.
NOAO has the skills and organizational structure to provide such a facility, and
plans to work with the community to make sure the design of the array meets a
broad range of requirements. Once the basic array is completed, the way will be
cleared for the advancement of interferometric astronomy: the future lies in the
methods of measuring amplitude and phase and thence reconstructing the image.
With the national facility available, university groups would be in a good position
to develop the new correlators and interferometric methods demanded for the best
possible interferometry. We foresee the test facility as the nucleus of the
community effort required to develop this important new branch of science.
IV. CORE PROGRAM

Responsibility for carrying out research and development programs within NOAO is assigned to four major divisions. Current programs and long range plans for each of these divisions are described in the sections that follow. One consequence of the formation of NOAO has been a much greater degree of coordination and cooperation among divisions. For example, the infrared instrumentation program in Tucson is headed by a member of the ADP and provides instrumentation for KPNO, CTIO, NSO, as well as for ADP. KPNO provides maintenance for solar facilities on Kitt Peak. CTIO will take the lead in developing new CCD controllers for use throughout NOAO. By taking advantage of the talents and capabilities within each division we are able to make the most effective use of the resources available to NOAO.

A. Cerro Tololo Inter-American Observatory

Telescopes.

The telescopes and instrumentation available at CTIO are listed in Table IV. CTIO has the largest optical telescope in the Southern hemisphere, but it will probably soon be superceded by planned telescopes at both ESO and Las Campanas observatories. Already ESO has substantially more total aperture than CTIO. Furthermore, the demand for CTIO’s major telescopes exceeds the time available by more than a factor of two from proposals that the peer review process judges to be strong, high quality scientific projects.

An increasing number of pioneering research investigations could be instigated if larger aperture were available. Among these are studies of the evolution of galaxies and quasars, rapid time resolved spectrophotometry of transient phenomena such as x-ray bursters and eclipsing mass transfer binaries, and determination of the space densities and luminosity functions of low luminosity objects like white and brown dwarfs. There is thus a real justification for additional telescopes of 4-m to 5-m aperture and substantially larger. The anticipated development of 8-m mirrors for use in individual telescopes or arrays offers an opportunity to address these and many other problems. CTIO places the construction of an 8-m class telescope as its first priority during the next decade. CTIO staff plan to begin focusing on the design specifications that will best match the specific types of problems that we believe will be most valuable to attack.

The parallel development of a 4-m telescope to be situated at Tololo is also under consideration. Many of the scientific programs that stand to produce the most important results cannot now be carried out at the National Observatories because they require too large a fraction of the available time. These include survey programs which must observe a large number of objects, e.g., a redshift survey to determine the three-dimensional distribution of galaxies or QSOs, and the optical identifications of x-ray and radio sources. Surveys have a history of unearthing extremely important results (many classes of objects in the universe were discovered in large surveys: quasars, pulsars, x-ray binaries, molecular clouds, Seyfert galaxies, etc.). An avenue for pursuing this type of program may be open because of the interest some universities now have in placing telescopes at Cerro Tololo. We do not believe that it is wise to divert NOAO effort away from an 8-m project; however, we are encouraging universities interested in 4-m class telescopes to consider placing them in Chile. The scientific benefits that come from increased activity in one locale can be large for all of the organizations involved, as can be attested to from the development of Mauna Kea in Hawaii.
### TABLE IV

**CTIO Telescope/Instrument Combinations**

#### 4-m Telescope:
- R-C Spectrograph + GEC CCD (Air Schmidt Camera)
- R-C Spectrograph + 2D-Frutti (Folded Schmidt Camera)
- Echelle Spectrograph + GEC CCD (Air Schmidt Camera)
- Echelle Spectrograph + RCA, TI, or GEC CCD (Long Cameras)
- Echelle Spectrograph + 2D-Frutti (Folded Schmidt or Long Cameras)
- Prime Focus Camera + Photographic Plates
- Prime Focus Camera + RCA CCD
- Cass Direct + TI, RCA, or GEC CCD
- Rutgers Imaging Fabry-Perot + TI or GEC CCD
- ASCAP Photometer
- IR Photometer
- IR Spectrometer
- SBRC IR Array Imager

#### 1.5-m Telescope:
- Cass Spectrograph + GEC CCD (with UV-Fluorescent Coating)
- Fiber-Fed Echelle Spectrograph + GEC CCD (Air Schmidt Camera)
- Fiber-Fed Echelle Spectrograph + TI, RCA, or GEC CCD (Long Cameras)
- Coude Spectrograph + Photographic Plates
- Cass Direct + TI, RCA or GEC CCD
- Cass Direct + Photographic Plates
- Rutgers Imaging Fabry-Perot + TI or GEC CCD
- ASCAP Photometer
- IR Photometer
- IR Spectrometer
- SBRC IR Array Imager
- Filar Micrometer

#### 1-m Telescope:
- Cass Spectrograph + 2D-Frutti
- ASCAP Photometer

#### 0.9-m Telescope:
- Cass Direct + TI, RCA, or GEC CCD

#### 0.6-m Telescope:
- Standard Photometer

#### Curtis-Schmidt:
- Photographic Plates

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**Site survey and development.**

Cerro Tololo is an excellent Southern hemisphere site, and it is inevitable that either NOAO or other U.S. institutions will ultimately place more large telescopes in Northern Chile. Since the summit of Tololo is now fully occupied, alternative
locations must be explored. Fortunately other peaks exist on the AURA property which are already known from previous testing to be good telescope sites. Some of the equipment used for the NNTT site surveys has been sent to Chile including two Echosonders, thermal sensors, and a CID camera which will be used for seeing measurements. NOAO is in the process of building microthermal towers.

As funding permits, we will begin comparisons of Cerro Tololo with Cerro Morado and Cerro Pachon. A road to Morado already exists and testing of this site will be relatively straightforward and inexpensive. The results of the original CARSO survey in the 1960s showed Pachon to be a potentially superb site with its higher elevation (8,900 ft.). However, no road exists, and even rudimentary site testing there will require significant effort.

Development of Cerro Morado would be relatively simple, involving only minor road improvements and water and electricity. Cerro Pachon would require more effort, including an additional land purchase. The present AURA property line passes very near the Pachon summit, and the acquisition of some thousands of additional acres of land would be necessary to protect the site and allow for the construction of an access road. Obviously this alternative should be pursued only if warranted by superior test results involving seeing, extinction, and H₂O vapor. Development of either site should proceed only if a specific telescope project requires it, but the likelihood of this happening is sufficiently high that planning should begin now.

B. Kitt Peak National Observatory

Overview of the facilities.

The first of the AURA managed observatories was established at Kitt Peak, and telescopes at that site have been continuously in operation since 1959 when the #1-0.4-m telescope was first scheduled for use by visiting astronomers. The KPNO division of NOAO now operates seven nighttime telescopes, and there is relatively little overlap in their capabilities. The 4-m telescope is a general purpose telescope that is used in the optical and infrared, for spectroscopy and imaging. With the initial announcement of the availability of infrared arrays, the 2.1-m telescope during bright time became the most oversubscribed of all the Kitt Peak telescopes for the fall semester of 1987. This telescope is also used for low resolution spectrophotometry, CCD imaging, and coudé spectroscopy. The 1.3-m telescope is used for photometry during dark time, and with its chopping secondary is particularly well suited to measurements of extended objects with low surface brightness. In bright time it is used for infrared astronomy. The Burrell Schmidt is the only nationally accessible Schmidt in the Northern hemisphere that is equipped with prisms for spectroscopic surveys; this telescope is operated jointly by KPNO and Case Western Reserve. The coudé feed telescope was designed to send light to the coudé spectrograph at the 2.1-m telescope, thereby allowing use of the spectrograph when the 2.1-m is being scheduled for other programs. There are two 0.9-m telescopes. The #1-0.9-m is used almost exclusively for CCD imaging. The #2-0.9-m has two instruments—a single channel photometer system and an intensified Reticon scanner for spectrophotometry. The availability of very large apertures at the #2-0.9-m makes this telescope suitable for spectrophotometry of galaxies with large angular sizes.

Table V lists the Kitt Peak telescopes and summarizes the instrumentation available for each.
<table>
<thead>
<tr>
<th>KPNO Telescope/Instrument Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4-m Telescope:</strong></td>
</tr>
<tr>
<td>Prime Focus Camera Grism + Photographic Plates</td>
</tr>
<tr>
<td>Prime Focus Camera + CCD</td>
</tr>
<tr>
<td>R-C Spectrograph + CCD (UV Fast Camera)</td>
</tr>
<tr>
<td>R-C Spectrograph + Carnegie Image Tube System + CCD</td>
</tr>
<tr>
<td>R-C Spectrograph + KPCA (KPNO Photon Counting Array)</td>
</tr>
<tr>
<td>Cryogenic Camera</td>
</tr>
<tr>
<td>Echelle Spectrograph + CCD (UV Fast Camera)</td>
</tr>
<tr>
<td>Echelle Spectrograph + Carnegie Image Tube System + CCD</td>
</tr>
<tr>
<td>Echelle Spectrograph + KPCA (KPNO Photon Counting Array)</td>
</tr>
<tr>
<td>Infrared Imager + InSb Array</td>
</tr>
<tr>
<td>Infrared Photometry (Blue Toad 1-5 μm InSb), (CCCP 3-13 &amp; 20 μm Si:Ga &amp; Si:As)</td>
</tr>
<tr>
<td>Fourier Transform Spectrometer (InSb and Si)</td>
</tr>
<tr>
<td><strong>2.1-m Telescope:</strong></td>
</tr>
<tr>
<td>Gold Spectrograph + CCD (Wynne CJ Camera)</td>
</tr>
<tr>
<td>Gold Spectrograph + Intensified Image Dissector Scanner (Wynne CJ Camera)</td>
</tr>
<tr>
<td>Cass Direct + CCD</td>
</tr>
<tr>
<td>White Spectrograph + Photographic Plates</td>
</tr>
<tr>
<td>Mark I Computer Photometer</td>
</tr>
<tr>
<td>Infrared Imager + InSb Array</td>
</tr>
<tr>
<td>Infrared Photometer (Blue Toad 1-5 μm InSb), (CCCP 3-13 &amp; 20 μm Si:Ga &amp; Si:As)</td>
</tr>
<tr>
<td>Fiber Optic Echelle Spectrograph + CCD (Visitor Instrument)</td>
</tr>
<tr>
<td>Coudé Spectrograph #5 or #6 Camera + CCD</td>
</tr>
<tr>
<td>Coudé Spectrograph + Photographic Plates Cameras 2, 3, 5, or 6</td>
</tr>
<tr>
<td><strong>Coudé Feed:</strong></td>
</tr>
<tr>
<td>Fiber Optic Echelle Spectrograph + CCD (Visitor Instrument)</td>
</tr>
<tr>
<td>Coudé Spectrograph #5 or #6 Camera + CCD</td>
</tr>
<tr>
<td>Coudé Spectrograph + Photographic Plates Cameras 2, 3, 5, or 6</td>
</tr>
<tr>
<td><strong>1.3-m Telescope:</strong></td>
</tr>
<tr>
<td>Mark II Computer Photometer</td>
</tr>
<tr>
<td>Infrared Photometer (OTTO 1-5 μm InSb), (HERMANN 1-5 μm InSb), (CCCP 3-13 &amp; 20 μm)</td>
</tr>
<tr>
<td>Infrared Grating Spectrometer (Audrey InSb)</td>
</tr>
<tr>
<td>Infrared Bolometer (2-20 μm Ge:Ga)</td>
</tr>
<tr>
<td>Infrared Imager (InSb Array)</td>
</tr>
<tr>
<td><strong>Burrell-Schmidt Telescope:</strong></td>
</tr>
<tr>
<td>Direct Photographic or Choice of 5 Objective Prisms + Photographic Plates</td>
</tr>
<tr>
<td><strong>#1-0.9-m Telescope:</strong></td>
</tr>
<tr>
<td>Direct CCD</td>
</tr>
<tr>
<td>Black Spectrograph + Photographic Plates</td>
</tr>
<tr>
<td><strong>#2-0.9-m Telescope:</strong></td>
</tr>
<tr>
<td>Single Channel Automatic Filter Photometer</td>
</tr>
<tr>
<td>White Spectrograph + Direct Plates</td>
</tr>
<tr>
<td>White Spectrograph + Intensified Reticon Scanner</td>
</tr>
</tbody>
</table>
Telescopes with apertures other than the very largest often play a disproportionate role in the discovery of qualitatively new phenomena. Because they are less heavily oversubscribed, it becomes possible to schedule high risk or long term programs. For example, the 2.1-m telescope at KPNO has to its credit the following discoveries:

- Discovery of the first gravitational lens, 0957+561, by R. Walsh, R. Carswell, and R. Weymann.
- Discovery of the 100 Mpc$^3$ void in Bootes by A. Oemler et al, together with confirming follow-up observations.
- Discovery of the "Rubin-Ford Effect," namely that there are large scale motions superposed on the uniform Hubble expansion.
- Discovery of the "Butcher-Oemler Effect," namely that there are more blue galaxies at large redshift than nearby.
- Discovery of the Lyman $\alpha$ forest by R. Lynds.

The impact of the telescopes operated by KPNO can be measured by attendance at virtually any scientific meeting, by sampling copies of the Astrophysical Journal, or by reading the popular literature. The impact of KPNO, however, goes far beyond the work carried out at its own telescopes. NSO operates two solar telescopes on Kitt Peak—the vacuum telescope, which provides much of the basic monitoring data for the Sun including daily magnetograms, and the McMath, which is used for both solar observations and monitoring of stellar activity. In addition, there are telescopes on Kitt Peak operated by NRAO, including one of the antennas for the VLBA on the southwest ridge; by Steward Observatory of the U. of Arizona; and by the McGraw-Hill Observatory, which serves the U. of Michigan, Massachusetts Institute of Technology, and Dartmouth Coll. These facilities all benefit from the fact that KPNO pays for most of the costs of maintaining the mountain infrastructure.

The Kitt Peak staff takes justifiable pride in its service to the user community. All instruments are thoroughly calibrated, well documented, relatively user friendly, and reliable. No instrument is considered complete until the software is available to analyze the data. In recent years, we have come relatively close to achieving our goal of sending all observers home from the mountain with data reduced at least to the point where the instrumental signature has been removed.

Approximately 600 astronomers use KPNO telescopes each year. They range in background and experience from members of the National Academy of Sciences to graduate students. Approximately 20 percent of the users are from institutions that have major telescopes of their own but wish to make use of unique instrumentation. At any given time there are about 20 students carrying out observations for Ph.D. dissertations.

Future development.

NOAO believes that Kitt Peak can and should remain one of the premier sites for U.S. astronomy. The site is fully developed, is occupied by a large number of telescopes, and this concentration of facilities combined with easy access from a major city makes operations highly cost effective. Furthermore, recent
measurements suggest that Kitt Peak is a better site than we had realized. The median seeing at the 4-m telescope is currently 1.2 arcsec. The image quality at this telescope was previously seriously affected by the thermal environment of the dome. The measurements were made after we removed many obvious sources of heat and enclosed and cooled the Cassegrain cage to insulate the telescope from heat generated by electronics. Recently installed fans exchange the air in the dome every twelve minutes, and when resources allow we will cool the oil that coats the horseshoe. This latter step should improve the image quality still further.

The extensive publicity given to problems of light pollution has had the positive effect of inducing all of the relevant counties in Arizona to adopt lighting ordinances requested by the astronomy community. The publicity has had the negative effect of persuading many astronomers that the problems experienced at Kitt Peak are already critical. Stimulated by theoretical calculations by R. Garstang at the U. of Colorado that showed that Kitt Peak should still be a good dark sky site, we have undertaken a series of measurements of sky brightness. In the V magnitude, measurements show that Kitt Peak is only about 0.10 mag brighter than the value expected for a completely dark sky, and Garstang's calculations based on predictions of population growth by the State of Arizona suggest that even in 2035 Kitt Peak will be only 0.26 mag brighter than the natural sky background at the zenith, and these calculations do not take into account the effect of the lighting ordinances. By the year 2035 astronomy requiring extremely dark skies will probably be carried out primarily on Mauna Kea, in Chile, or even possibly from space. Kitt Peak will still, however, remain satisfactory for most programs, and will be especially well suited for high resolution spectroscopy and near infrared observations.

While we do not propose to build 8-m class telescopes on Kitt Peak, we do believe it would be cost effective to upgrade the facilities offered to the Kitt Peak user community. Two possibilities that are actively being explored are the construction, in collaboration with universities, of a 3.5-m telescope, at which NOAO's share of the observing time would be devoted to spectroscopy, and of a telescope that would support synoptic programs, including monitoring of stellar activity. Details of these possible projects are listed under initiatives in this plan. Extensive studies over the past few years have shown that very little money is saved by closing one or two telescopes at a site because the infrastructure costs are nearly independent of the total number of facilities in operation. Adding telescopes requires relatively little additional funding for the same reason, and placing new telescopes on Kitt Peak would take advantage of that fact.
<table>
<thead>
<tr>
<th>Observatory</th>
<th>Altitude</th>
<th>Year</th>
<th>U</th>
<th>B</th>
<th>V</th>
<th>R</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitt Peak</td>
<td>zenith</td>
<td>1986-7</td>
<td>22.84</td>
<td>21.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>1986-7</td>
<td>22.71</td>
<td>21.64</td>
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<tr>
<td>(CCD obs)</td>
<td>zenith</td>
<td>1984</td>
<td>21.93</td>
<td>22.47</td>
<td>20.91</td>
<td></td>
<td></td>
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<tr>
<td>Predicted</td>
<td>zenith</td>
<td></td>
<td></td>
<td></td>
<td>21.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sac Peak</td>
<td>zenith</td>
<td>1978</td>
<td>21.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>1978</td>
<td>21.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>zenith</td>
<td>1978</td>
<td>21.88</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td></td>
<td></td>
<td></td>
<td>21.68</td>
<td></td>
<td></td>
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<tr>
<td>CTIO CD</td>
<td>zenith</td>
<td>1987</td>
<td>21.75</td>
<td>22.55</td>
<td>21.75</td>
<td>20.85</td>
<td>19.9</td>
</tr>
<tr>
<td>Mauna Kea</td>
<td>zenith</td>
<td>1987</td>
<td>23.05</td>
<td></td>
<td>21.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted</td>
<td>zenith</td>
<td></td>
<td></td>
<td></td>
<td>21.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:


3 The number quoted for Sacramento Peak is taken from Schneeberger et al (1979, P.A.S.P., 91, 530), and is the average of 5 nights within 4 days of new moon. Another 5 observations were taken in June 1978, and are presumably contaminated by the galactic plane at the zenith. Including the June observations gives an average sky brightness of 21.77 for nights within 4 days of new moon. The darkest night measured on Sacramento Peak gave V = 21.91. Measurements on Sacramento Peak, however, were taken in 1978, only about two years before solar maximum.

4 A. Walker 1987, NOAO Newsletter No. 10.

5 D. Tholen 1987, private communication.
C. Instrumentation for KPNO and CTIO

Instrumentation plays at least as important a role in determining the performance of telescopes as does aperture, and the development of new instrumentation at NOAO is currently limited by funding not by technology. Large format electronic detectors for the infrared and optical regions of the spectrum are far more expensive than photographic plates. Large format detectors also require that substantial computing power be available at the telescope. The costs of vital instruments, such as multiple object spectrographs and infrared spectrometers, can easily fall in the range $500,000 to $1,000,000. Nevertheless, we believe that increased support for instrumentation is the single most cost effective step that can be taken to improve the scientific productivity of NOAO telescopes.

Because we consider the development of new instrumentation, along with the associated computer control systems and data reduction facilities, one of the most critical aspects of the program for CTIO and KPNO we outline our proposed plans in some detail.

The main focus of the program at both observatories is the incorporation of two-dimensional digital detectors, both in the optical and the infrared, into existing instruments and into a new generation of imagers and spectrometers designed for efficient throughput and matched to modern detectors. We also need to make improvements in telescope performance, increase the sensitivity of TV acquisition systems, and add to the computer power available at the telescopes. The instrumentation program for both CTIO and KPNO is described below; the efforts of the two observatories are so similar and so closely coordinated that there is in effect a single NOAO program for nighttime astronomy. The science justification for the instruments that are planned has been given in program plans submitted earlier to the NSF.

Infrared instrumentation.

For the first time sensitive infrared array detectors are now commercially available. They promise to have an impact on the field that is greater than that of optical CCDs when they were introduced in the late 1970s. CCDs represented "mere" 100-fold improvements in efficiency over previously available devices, whereas in the infrared there have been up until now no true array detectors whatsoever.

NOAO has taken a leading position in this field, both at a national and international level. The infrared array program is also probably the most successful example of a NOAO program involving collaboration between the different divisions on development and testing of major new instrumentation. The ability to draw on the resources and expertise of all of NOAO is certainly one of the reasons for the overall success of the project.

The infrared imagers for KPNO and CTIO went into regular operation 1 September 1987 for the user community. These devices are revolutionizing infrared astronomy. They are based on a 58 x 62 InSb array manufactured by Santa Barbara Research Corporation.

Each of the 3600 elements in the array outperforms previous single element detectors!
There are at least four areas where NOAO should press ahead in developing IR instrumentation during the next five years: (a) expansion of present near-IR imaging capabilities, (b) development of improved infrared spectroscopic capabilities, (c) extension of imaging and spectroscopic capabilities to the mid-IR (10 - 20 μm), and (d) evaluation of new detector materials.

**Expanded near IR-imaging capabilities.** The present imagers were designed to operate through broadband filters only. A simple and versatile way to expand the capabilities of the imagers is to install a variety of modular prefilters on an "optical bench" between telescope and imager. This optical bench must be cooled to avoid degradations in performance arising from background radiation.

NOAO has purchased narrow band filters at the wavelengths of important spectral features, a novel "linearly variable filter" tunable over the important wavelength range 2.1 - 2.34 μm (which contains lines of atomic and molecular hydrogen, helium, and carbon monoxide), and the components for a polarimeter and a stellar coronagraph.

We are also testing the first ever IR grism, designed and built at NOAO, in the filter wheel of the KPNO imager. These modifications and additions immediately enhance our capacity to make innovative observations. Unavoidably, they also increase the pressure on the availability of the array detectors. Additional pressure comes from entirely reasonable and often exciting requests for use in speckle, adaptive optics, and solar work.

It is clear that we must plan to provide more infrared imaging capability within NOAO because the scientific returns will be very great.

**Infrared spectroscopy.** KPNO has been the leader in the field of high resolution infrared stellar spectroscopy, but such work has been restricted in the past to observations of comparatively bright objects and to Northern hemisphere objects. The enormous gains in efficiency realizable with infrared arrays allow one to contemplate building instrumentation sensitive enough to observe many fainter galactic objects, and even extragalactic objects.

An existing KPNO IR spectrometer has been upgraded to use a 58 x 62 InSb array at resolutions of 100 or 1000 from 1 - 5 μm. Telescope tests began in the fall of 1987. This instrument will function in a long-slit mode. The CTIO 8-channel IR spectrometer will be upgraded to an array detector in the first half of 1988.

NOAO further plans to build a higher resolution spectrometer, with resolution up to 100,000 using an echelle grating. Generic arguments based on detector performance are equally persuasive about the utility of this instrument, and again we anticipate extraordinary improvements.

The cryogenic echelle spectrometer, a formidable engineering challenge, will be designed to accommodate both currently available and "next generation" detectors. Because of the relatively low light levels and the large numbers of spectral elements, the power of this instrument can be greatly enhanced through the use of larger format and more sensitive arrays. While the cryogenic echelle is being built in Tucson it is important that the capability it provides be available at both CTIO and KPNO, either through sharing the instrument or, if funding allows, building a duplicate.
Detector research and development. NOAO’s heavy involvement in the development of the SBRC InSb 58 x 62 array detector for infrared astronomy was directly responsible for the early implementation of these devices at our telescopes, and we firmly intend to work with the infrared community and with manufacturers to continue a vigorous program of detector evaluation and implementation. Indeed we wish to identify this pursuit as a great strength of the NOAO IR program. We project that, as a minimum goal, a 256 x 256 array with one-quarter the read noise of the present device will be operational within five years. Evaluation of alternative detector materials will continue to be an important component of our program.

NOAO will also pursue array technology suitable for operation at 10 μm wavelengths. We plan to begin tests of Impurity Band Conduction (IBC) array detectors in the near future. These devices are likely to be suitable for installation in cameras and spectrometers, and we anticipate a need to build such instruments beginning in FY 1991. Some experimental arrays are already available. Although they cannot now be exported to Chile, we expect this restriction will eventually be lifted. CTIO is developing the capability to deal with the high data rates produced by these long wavelength detectors, and initial testing will take place at KPNO.

In summary, the needs of the IR program for the period FY 1989 - 1993 are:

- To consolidate its present success in near-infrared (1 - 5 μm) imaging by construction of more array-based cameras.
- To implement array-based near-infrared low and moderate resolution spectrometers at both KPNO and CTIO; also development of a high resolution spectrograph for joint use at KPNO and CTIO.
- To pursue and implement improvements in near-infrared array technology including larger format, smaller read noise, and alternate detector material.
- To design and build the cryogenic optical bench.
- To develop detector arrays for 10 μm.
- To build cameras and spectrometers to work at 10 μm.
- To investigate and implement solutions to problems of increasing data rates.

At present levels of funding, it is not possible to pursue both the "consolidation" and "innovation" components of this program, and that is one reason that we place so high a priority on increasing the budget for instrumentation.

Optical instrumentation.

The goal of the development plan for optical instrumentation is to incorporate advances in technology for detectors and fiber optics, in order to cover much larger fields of view for imaging and for multiple object spectroscopy. With an eye to future large telescope development, NOAO proposes a new generation of focal plane instruments for the current telescopes, including arrays of CCDs and fiber-fed, bench mounted spectrographs. At the time of this writing a number of commercial development efforts are underway to produce scientific grade, low light CCD imagers, most notably at Tektronix. Although none of these efforts has yet been
fully successful, we remain confident that NOAO will receive a new generation of imagers with 25 to 30 μm pixels during the period of this plan.

Many of the programs described in this plan require multiple object spectroscopic capability. Bench mounted spectrographs will be fed by multiple optical fibers with automatic positioners in the focal planes of the 4-m telescopes. The need for new spectrographs is mandated by the use of fibers, which have an effective output focal ratio of f/4 to f/5, not a good match to the f/8 spectrographs currently available. Further constraints on the systems are long slits to accommodate 50 to 100 fibers and cameras that will probably be optimized for detectors with 50 to 60 μm resolution elements. For work on very faint objects, multi-slit masks have been available at KPNO for the cryogenic camera for several years. Its limitations are field of view and crowding from directly projected slitlets.

Design trade-off studies are now underway, and the initial concepts at CTIO and KPNO are somewhat different. The KPNO design calls for use of the 45 arcm-min field at the R-C Cassegrain focus. One advantage of this approach, besides ease of guiding and the presence of calibration sources, is that the scale allows the use of 300 μm diameter fibers. These are likely to be easier to end polish and handle than the 100 μm fibers required at prime focus. The concept for the positioning mechanism is a 14-inch square commercial precision x-y stage, with a steerable arm used in the manufacture of micro-circuitry. The fiber ends will be placed in a magnetic "button," with a lens/prism coupling as a focal ratio compensator. This scheme allows for the addition of more fibers as demand warrants, in contrast to a dedicated positioner for each fiber. The goal is to assemble a working system primarily from commercially available components, with a view toward sharing development experience with other observatories undertaking similar projects, and to provide the basis for a large scale instrument for the proposed new 3.5-m telescope.

CTIO has begun development of fiber-fed spectrographs to be used both at the 4-m and 1.5-m. At the 4-m, we plan to use the prime focus with an atmospheric dispersion corrector. A multi-fiber (24 pairs) feed will be sent to environmentally isolated rooms containing bench mounted spectrographs. These spectrographs will be extremely stable thus permitting radial velocity work. Since space and weight are no problem we will be able to build the spectrographs to be very stiff and optimized for as little light loss as possible. We plan to offer both a regular low dispersion spectrograph and an echelle. With optimized optics, up to 25 percent throughput should be achieved in the telescope/spectrograph/detector systems.

These spectrographs will sit in the 4-m building, and similar ones will be constructed for the 1.5-m telescope. We are experimenting with using the present 4-m telescope echelle as a radial velocity meter, and tests have been done with the echelle using no cross dispersion. A very stable spectrograph coupled with rather simple data reduction techniques will produce an instrument competitive with CORAVEL, the ESO radial velocity instrument.

By adopting different approaches CTIO and KPNO can evaluate the various options for fiber feeds on telescopes. CTIO has chosen the prime focus for its wide field (> 50 arcm-min), fast f/ratio, and flat field. CTIO is interested in utilizing fast f/ratios (f/2.7) to achieve minimum focal ratio degradation within the fibers. The flat field provided by the prime focus corrector allows placement of the fibers without worrying about focus degradation across the field. KPNO has chosen the R-C focus for its large plate scale, slower f/ratio, lack of need for a corrector, ease of access, and shorter required fiber length to reach the coude room. Both
approaches have advantages, and in this case it seems appropriate to have complementary rather than duplicate instruments.

CTIO also plans to install a grism at the 4-m telescope prime focus with a large format detector to do very deep spectroscopic searches. In addition, we plan to mount a large format CCD on the CTIO Curtis Schmidt telescope. With 15 μm pixels, the pixel size will be ideally matched to the seeing disks. Fast sky-limited frames will be taken for synoptic studies such as discovery of novae in external galaxies or deep prism frames for emission line object searches.

The other major thrust of the KPNO program is wide-field CCD imaging. If a large format (2048 x 2048) chip can be produced, it will increase the useful area of a single exposure by a factor of 16. Even this substantial gain does not begin to fill the field available at the prime or R-C foei. With the next generation of large telescopes promising physically very large focal planes, we must actively support the development of mosaicing techniques. One approach may be to participate in a consortium to promote industrial development of buttable arrays with new mask configurations for two-sided pinouts. We must also participate with the manufacturers in searching for successful thinning and packaging procedures, as well as anti-reflection coating and permanent UV sensitization techniques.

The new solid state imagers require more powerful controllers. A single large format chip generates 8 Mbytes of data per image. Under those circumstances storage of multiple calibration frames and images in the intermediate stages of routine reduction becomes impractical. A new controller system is under development jointly by CTIO and KPNO that employs modern hardware and is capable of handling large formats and performing routine reduction processes such as removal of bits, trimming, and flat field correction. The system must handle multiple quadrant and multiple chip readout, frame reconstruction, and storage. Further modifications will also be required for the camera head electronics, especially the replacement of amplifiers with ones of very low noise performance to match that of the CCD on-chip amplifiers. New chip pinout schemes will certainly require control circuitry modifications. In addition, dewar windows for large format and array mosaics must be designed, probably as corrector elements customized to the individual telescope’s focal plane. Several other observatories also plan to develop new controllers. We have had discussions with them, and if there is sufficient interest will host a workshop to interchange design information.

Planning is under way within NOAO for ground-based support of space observations. The long range plan period should see the launch of the Hubble Space Telescope (HST), EUV Explorer, the ASTRO Ultraviolet Payload, and possibly the ROSAT x-ray facility. As proven with IUE, Einstein, and IRAS, a satellite database generates a very strong demand for follow-up with ground-based facilities. The limited access of any individual investigation to HST will probably lead to small observing programs with many single object or partial night requests. This situation requires a new flexibility in program scheduling, with the possibility of staff observers selecting from a queue of programs. A development to help in implementing such a flexible schedule is to have imaging and spectroscopic capabilities easily interchangeable. The specific plan is to make imaging dewars mountable at the TV viewing ports of the KPNO 4-m and 2.1-m telescopes, while a spectrograph is on the telescope. The CCD is addressable by the viewing field flat mirror, allowing filtered imaging in lieu of, or in combination with, spectroscopic observations. This desirable option will require the control system to maintain the additional dewars at temperature and keep separate track of the imaging calibration frames.
The levels of polarization observed in astronomical objects are small, typically less than 10 percent. Nonetheless, the measurement of the wavelength dependence, and for extended objects the spatial variation, of this polarization can often provide information which cannot be obtained in other ways. NOAO presently does not have any polarimetry system, but in the next several years CTIO plans to construct a general purpose polarization module, which would permit existing and future Cassegrain focal plane instruments on the CTIO 4-m telescope to be used for imaging polarimetry and/or spectropolarimetry.

The Rutgers imaging Fabry-Perot camera is presently on loan to CTIO and already has provided several interesting results. We plan to continue to offer an imaging Fabry-Perot capability, perhaps collaborating with Rutgers or another university in the construction of a second generation instrument for use with larger format CCDs.

**Telescope improvements.**

New instruments often demand higher performance from telescopes in terms of pointing, image quality, tracking, offsetting, and rastering. Accordingly, we have an ongoing program of upgrading NOAO telescopes.

Substantial effort is being devoted at both CTIO and KPNO to work designed to improve image quality. A 20 percent improvement in the average seeing is equivalent to a 10 - 20 percent increase in the telescope primary mirror diameter. We must give our telescopes an environment that enables them to perform up to the full potential of the sites. Experience within NOAO and elsewhere shows that with sufficient care one can eliminate many of the sources of "dome seeing." Closing the Cassegrain cage, adjusting air flow into or out of the domes, mirror temperature stabilization, and cooling of the oil for the hydrostatic bearings are all projects that will improve image quality, and work is in progress at both observatories.

A major task for KPNO and CTIO is to complete the installation of Sun IRAF workstations at all nighttime telescopes. Our goal is to put at every telescope an image processing system that includes everything an observer needs to reduce data (IRAF, cpu, display, disks, and tape drive) in real time. The advantages of having such power at the telescope are: (1) the observer can immediately determine the quality of the data being obtained (S/N, photometric repeatability, velocity errors, etc.) for a guide in planning the next observations; (2) it considerably reduces the bulk of data that one must take home; and (3) the observer can leave the telescope with the astrophysically interesting parameters (velocity, redshift, magnitude, etc.) already determined. The workstations will also be essential to handle the data from large format detectors (Tektronix 2048 x 2048 CCDs) when these devices become available. The current CCD computers are too limited to handle anything but taking the data for such large detectors.

The standard mountain system consists of a Sun 3/280 cpu, 16 Mbyte memory, 1.1 Gbyte disk, floating point accelerator, 6250/1600 bpi tape drive, color display, and laser printer. Systems have been installed at three telescopes at CTIO and at the KPNO 4-m and ordered for the KPNO 2.1-m telescope. Unfortunately, we cannot afford to provide this standard system at the remaining telescopes in the foreseeable future. Accordingly, we plan an initial implementation with small systems, which can be upgraded subsequently to meet the needs of larger format detectors when they become available. These systems will be linked to the standard systems at the larger telescopes via Ethernet. The exact hardware to be purchased will depend on what is available at the time that funding is identified.
CTIO maintains several computers with different operating systems. This diversity has occurred because of changing technology and the long development time for implementation of computing facilities. Some of the computers are now rather old and thus slow, and need replacing. The observatory has decided that one of the major projects for the next five years should be the completion of an integrated system by phasing out some of the old hardware, e.g., the MV/8000, and acquiring new machines that are compatible with the remaining computers. This project will also network all of the computers in La Serena and on Tololo.

Networking is also planned for Kitt Peak computers. Communications links between computers are desirable for many reasons, including simplifying software maintenance, transmitting data, making available a single shared list of standard stars to all telescopes, and funneling maintenance and trouble reports to a central machine. Connecting the various mountain computers together is a necessary step toward remote operation; communication with downtown facilities will be via microwave link, which will be too expensive to duplicate for each telescope.

At both observatories we plan to use Ethernet, which is the (current) industry standard for communication between nearby computers and provides 10 megabits per second (Mbs) maximum data transfer rate. At KPNO we plan to use fiber optics, which is lightning immune, can be used over the relatively long distances between telescopes, and can handle data rates far in excess of 10 Mbs. The fiber network can also be used to connect the various domes with voice and television, and in particular will make it possible to transmit all-sky cloud cover images from one central television camera to all observers.

Both CTIO and KPNO plan to interconnect mountain and downtown computer systems via individual microwave links. Recent developments in the microwave market make it possible to provide data links at moderate cost to accommodate all current requirements, with expandability to meet most foreseeable needs as well. A high bandwidth communications link will allow us again to support remote observing. KPNO was a leader in the development of remote observing, but left the field because of telephone costs. A direct mountain link will provide access via Bitnet, Arpanet, Astronet, and the other networks which we are joining to virtually all astronomy centers in the U.S. and many around the world. The cost of these networks is very low, generally not dependent upon volume of usage, and a significant bandwidth is available at night. Direct data transmission at both CTIO and KPNO is also a must for cost effective archiving. The greatest potential cost item in setting up an archival system is personnel, since even minimal manual intervention in the archiving process is likely to require several FTEs. Support of archiving is impossible within present budget constraints and present technology. A data link to the central computer system, with the capacity to handle the total data volume, will permit highly automated staging, editing, indexing, and archiving of data. A microwave link offers additional advantages in terms of balanced loading of mountain and downtown computers. In the case of KPNO, there would be access to the San Diego Supercomputer Center (SDSC) Cray computer.

As communications costs decrease sometime within this time period, it should become cost effective to establish a dedicated voice/data link between La Serena and Tucson. This will allow transmission of modest quantities of data at low cost between the two sites, as well as allowing some astronomical observations to be made remotely or in a remotely aided service observing mode.
Discussions within NOAO have led to a plan for common software at the observatories to handle real time telescope control and instrument control. A consensus has been reached regarding the preferred development path using 68020 based computers running the VRTX real time operating system with programming done in the "C" language. KPNO and CTIO prefer to use VME bus hardware because VME is used in our Sun workstations. VRTX has already been purchased for the observatories, and in fact is currently running at the Sacramento Peak Vacuum Tower Telescope. This standardization will considerably improve the reliability and maintainability of all of our telescopes. In addition to the standardization we will also be implementing other features. These include star catalogs on line and closer integration of telescope control, autoguider control, and data acquisition computers.

Field acquisition TV systems form an integral part of the modern telescope facility. As the demand for faint object observations increases, the need for more sensitive TV acquisition systems also increases. It is clear that the ISITs used at the NOAO telescopes do not reach sky limited performance levels and are usually far from reaching that level.

In an effort to improve our acquisition systems, KPNO and CTIO propose to work together and to target several areas for investigation. First, we need to identify a suitable detector for use in the next generation of acquisition systems. It is likely that some in-house development will be required, since we have been unable to find commercially available systems that are suitable. The new systems must both be sensitive and must have a flat response over the field of view. Secondly, efficient transfer optics (or none at all) are vital to overall progress. Another problem is that our current TV acquisition systems do not give us target integration. The ability to build up the signal prior to readout is a distinct advantage.

Palomar Sky Survey.

The Palomar Sky Survey has been an extraordinarily valuable resource for astronomers during the past 30 years. A new survey is being undertaken, and will be an even richer source of material because it will be in three colors instead of two and because it will be taken on emulsions of a higher detector quantum efficiency, which will give a higher information content. The survey is expected to reach objects some two magnitudes fainter than the emulsions used in the original survey; these fainter limits may be expected to increase the number of stars by a factor of 1.7 and the number of galaxies by a factor of 6.6 over those visible on the original survey. The higher information content of these newer emulsions also will allow more effective microphotometry of extended sources; the addition of the new survey after a lapse of 30 years will allow differential studies, including measurements of proper motions, between the two sets of plates; the new survey will allow the determination of precise positions for observations of objects that are fainter than the limits of TV acquisition systems.

NOAO has a Grant two-coordinate measuring engine linked to a computer that allows a user to get positions of celestial objects to better than 1 arcsec accuracy. We also have a PDS microphotometer with a Fairchild CCD replacing the normal detector. Under computer control this system can be used to scan plates automatically and to obtain precise positions, magnitudes, and surface brightnesses.

No other publicly available facilities in the U.S. have the same combination of survey material, plate measuring capability, and easy user accessibility. It is
essential that the existing resources be upgraded by the purchase of the new Palomar survey. This survey will cover 894 fields and have three colors: IIIa-J (blue-green), IIIa-F (red), and IV-N (infrared). The price of glass copies, which are required for accurate astrometry, is likely to be about $150,000 per color, so that the total cost is of the order of $450,000—a sum clearly beyond the scope of most university astronomy programs. Therefore, the collection is likely to be a significant community resource. In addition, we plan to buy film copies for both Tucson and Cerro Tololo and will have to provide for mounting and storing both film and plates.

D. National Solar Observatory

The National Solar Observatory operates facilities on two sites—Sacramento Peak and Kitt Peak—for both solar and stellar astronomy. In addition, NSO has taken the lead in formulating and implementing the GONG project, which is designed to probe the interior structure of the Sun by analyzing solar oscillations.

The facilities operated by NSO play a unique role in solar astronomy in this country. While the nighttime telescopes managed by NOAO are matched by comparable facilities in universities, the small but active solar community in the U.S. is largely dependent on NSO facilities for observational solar physics.

Facilities.

The Vacuum Tower Telescope (VTT) is the primary facility at Sacramento Peak and consists of an evacuated reflecting telescope with a 76-cm entrance window. It is designed to provide high spatial resolution images of the Sun. Primary analyzing instruments consist currently of a 12-m echelle spectrograph, a universal spectrograph, a universal birefringent filter, other specialized birefringent filters, a multi-diode array, and some small, specialized instruments. Horizontal and vertical optical benches are available at two exit ports for mounting temporary experiments.

The high quality spatial resolution possible with the VTT allows important studies of fine details of the solar atmospheric structure, including prominences. Most experiments seek high spatial/spectral resolution spectra, and/or high spatial resolution narrow spectral band images. Quiet Sun studies are concerned mostly with energy transport and atmospheric heating as produced by small and large scale convection and wave motions in the photosphere, chromosphere, and transition region. Small scale intense magnetic fields and associated velocity flows in the quiet Sun are an important area of research. The complex plasma processes that characterize active regions remain poorly understood. In evolutionary terms they are characterized by flux emergence, adjustment of active region structure to rearrangement of the subphotospheric field, and decay. The formation of sunspots and pores in active regions and their morphological characteristics continue to pose many fundamental questions in solar physics. Flare processes are even more complex, because of the rapid, localized release of large amounts of energy. In this area of research also, the magnetohydrodynamic complexities are such that considerable interpretive uncertainties remain, and much, much more needs to be done.

The John W. Evans Solar Facility (previously called the Big Dome) at Sacramento Peak has two 40-cm aperture emission line coronagraphs, other smaller telescopes mounted on an 8.2-m photoelectrically guided spar, and a 30-cm coelostat. The main coronagraph and the coelostat are each designed to feed light to a variety of
analyzing instruments including a 13-m Litrow spectrograph, a spectroheliograph, a universal spectrograph, and a coronal photometer. The facility also includes a so-called Doppler-Zeeman analyzer telescope.

As with the Vacuum Tower Telescope, experiments carried out at the Evans Solar Facility cover a broad range of solar phenomena, with emphasis on observations of the emission corona, prominences, and disk features where the low scattered light of a coronagraph is essential. Certain observations are routinely recorded on a daily basis and provide a record of changes on the Sun—measurements important both for short-term as well as long-term studies.

Coronal studies cover practically the full regime of visible coronal emission phenomena. Examples are the physics of loops (heating mechanisms, electric fields, flow velocities, stability, evolution, reconnection polarization), coronal holes (morphological characteristics, flows, temperature, sector boundaries), transients, streamers, and general morphology. Measurements of the emission of three coronal lines are transmitted daily to national centers that are concerned with forecasting solar activity. By taking advantage of the polarization-free and low scattered light instrumental characteristics of the main coronagraph at the primary focus, studies of the polarization of prominence emission allow vector magnetic fields to be deduced. The same techniques can be applied to the study of sunspots.

The Hilltop facility, also at Sacramento Peak, has a wide variety of small telescopes dedicated to synoptic programs. The instrumentation includes a white light flare telescope and a 20-cm aperture, two emission line coronagraphs. The set of Hilltop instruments automatically records flares, sunspots, coronal, and other solar phenomena on a daily basis from sunrise to sunset.

In general, the telescopes at Hilltop provide synoptic data that constitute a monitor of solar activity on a time scale of one minute. The white light flare telescope provides important diagnostic data, which together with other optical, ultraviolet, and x-ray measurements, yield information on chromospheric radiative losses and flare energy transport mechanisms.

The McMath Telescope complex at Kitt Peak includes the McMath Telescope itself, with its three separate light paths. The Solar Vacuum Telescope and the small Razdow patrol instrument comprise the second solar complex on Kitt Peak. At the McMath Telescope the available solar instrumentation includes a long focal length, high dispersion spectrograph, an infrared spectrograph, and the Fourier Transform Spectrometer (FTS). The Solar Vacuum Telescope features a multi-channel magnetograph, soon to be upgraded for the accurate measurement of velocity fields.

The work at this facility centers around its capability for high spectral resolution and for infrared work. The solar-stellar community makes use of a high signal-to-noise CCD spectrograph for the study of solar-like phenomena on stars. The main spectrograph and FTS are used for studies of solar line profiles, e.g. the relativistic shift of lines in the solar spectrum. In addition an active program of laboratory spectroscopy is carried out at the FTS. The McMath Telescope, with its large aperture and all-reflecting optics, is an ideal instrument for infrared work and some exciting results have been obtained there recently in this area. The Solar Vacuum Telescope, supported in part by NASA, is used for magnetic observations of the solar surface and \( \lambda \) 10830 spectroheliograms. Oscillation observations are also carried out there from time to time.
Table VII summarizes the facilities operated by NSO.

Future directions.

**Solar oscillations.** The highest priority program within NSO is the GONG project, which is on schedule and on budget. The community, which will share in the scientific return from this powerful diagnostic tool, is participating enthusiastically in the definition and planning of the program. This project is described later on in this Chapter.

The Vacuum Tower Telescope at Sacramento Peak and the Vacuum Telescope at Kitt Peak are both used by NSO staff and visitors in studies of the global oscillations of the Sun. In addition NSO has recently put into service for such observations the Fourier Tachometer, which is located in Tucson. This instrument, developed in collaboration with the High Altitude Observatory, is ideally suited for full disk, low amplitude velocity studies of p-mode oscillations in the Sun. This instrument is considered to be an interim solution for providing the community with a specialized velocity measuring device in a clear site until the GONG is operational in a few years.

The spectromagnetograph at the Vacuum Telescope is currently being upgraded to facilitate the study of low amplitude velocity fields on the solar surface. This measurement will become a part of the synoptic observations at this telescope and will provide data for the study of convection and other velocity fields. The high angular resolution afforded by this instrument will be a unique aspect and will provide valuable information to be used in research on the structure and dynamics of the solar surface and interior layers.

**Small scale physical processes.** One of the most important avenues of solar research is the study of hydrodynamic and magnetohydrodynamic processes in the solar atmosphere. In collaboration with the High Altitude Observatory (HAO), NSO is working on defining and improving the polarization characteristics of the Vacuum Tower Telescope at Sacramento Peak. HAO will build a Stokes polarimeter to be used at this telescope for high resolution observations of small scale magnetic features. The need to understand solar magnetohydrodynamic processes at small scale will ultimately require a large aperture, low polarization telescope of a new and radical design. The international organization known as LEST (Large, Earth-Based Solar Telescope) plans such a telescope within the next few years. Already NSO staff have contributed significantly to the telescope design and other aspects of the program. We discuss this initiative in detail in Chapter III.

The NSO solar-stellar program. The NSO scientific program extends to the study of solar type phenomena on other stars. The links with solar physics are not only in the science--many solar phenomena are seen in solar type stars--but also in the synoptic approach to observations, which has been used successfully in solar applications for many years by solar physicists.

An active stellar community group has formed to make known its instrumental needs in this area and to define an improved stellar synoptic capability. This group, called SYNOP, held a workshop last year to discuss its needs and plan for the future. The decision was made to proceed with the design of a fiber-fed high resolution spectrograph, which would be transportable and would be used eventually on a large aperture (2-m to 4-m) telescope dedicated during a substantial fraction of the time to synoptic observations. This proposed initiative is discussed in more detail in Chapter III.
| **TABLE VII** |
| **NSO Telescope/Instrument Combinations** |
| **Vacuum Tower Telescope:** |
| Echelle Spectrograph |
| ESG Slit Jaw Camera System |
| Universal Birefringent Filter |
| Universal Spectrograph |
| Stabilized Spectrograph |
| Computer System |
| Horizontal Optical Bench |
| Vertical Optical Benches |
| Multiple Diode Array |
| Correlation Tracker |
| Branch Feed Camera System |

| **John W. Evans Solar Facility:** |
| 40-cm Coronagraph |
| 30-cm Coelostat |
| Large Spectrograph |
| Spectroheliograph |
| Dual Camera System |
| Universal Spectrograph |
| Coronal Photometer |
| Doppler Zeeman Analyzer |
| Computer System |
| Bit-Slice Processor |

| **Hilltop Dome Facility:** |
| Spar |
| Hα Flare Monitor |
| White Light Telescope |
| Full Limb Coronagraph |
| Sunspot Drawing Telescope |
| White Light Flare Polarimeter |

| **McMath Telescope Complex:** |
| Optical Systems |
| Vertical Spectrograph |
| 1-m Fourier Transform Spectrometer (FTS) |
| Solar-Stellar Spectrograph |
| Semi-Permanent Observing Stations |

| **Solar Vacuum Telescope:** |
| 512-Channel Magnetograph |
| Synoptic Data Available in Digital Form |

| **Razdow** |
| **Fourier Tachometer** |
Solar cycle studies. The nature of the activity cycle is not understood, and much of the effort in this field goes into long term synoptic studies similar to those in the solar-stellar area. The aging collection of solar synoptic telescopes currently used to provide the bulk of the low resolution synoptic observations should be replaced by a modern, research grade, worldwide network of small synoptic instruments. There is considerable interest in this concept on the part of several government funding agencies, and also in several other countries that support research in this area. NSO will continue to play a leadership role in the definition of this worldwide program, and these efforts may result in a separate initiative in this area in the future.

Instrumentation.

Adaptive mirror project. Many of the basic physical processes in the solar atmosphere occur on spatial scales below 1.0 arcsec. For example, the interaction of convective motions with the small scale magnetic field patterns, which generates most of the fine structure we observe and which heats the overlying layers, can be studied in detail only with solar images that attain at least 0.3 arcsec resolution for at least several hours. This results in a constant struggle to achieve the highest possible angular resolution. A recent report commissioned by AURA has emphasized the importance of high resolution solar observations. NSO plans to mount an intensive program of instrument development, centered on adaptive optics, for research in this critical area. We view this as a prerequisite of any consideration of new large aperture solar telescopes.

Adaptive optics systems offer an attractive complement to space systems for subarcsec resolution. Indeed, NSO’s highest priority for instrumentation, after the GONG project, is the acquisition of a functional adaptive mirror for high resolution imaging and spectroscopy in the visible spectrum. In FY 1986 NSO began a program in adaptive optics, in collaboration with the USAF Geophysics Laboratory. The initial phase, the installation and testing of the Lockheed prototype system at the Sacramento Peak Vacuum Tower Telescope, has been completed. The Lockheed 19-element mirror definitely improves a solar image, but not as yet to the diffraction limit (0.2") of the Sacramento Peak Vacuum Tower Telescope. Our tests indicate that the basic principle of the Lockheed system is sound, but that several components and subsystems must be improved to realize diffraction limited resolution for extended periods, in moderate to poor seeing.

As a consequence of this initial experience, we now plan to expand this work with investigations of different types of mirror systems, piezo-electric and other actuators, reference interferometers and wavefront sensors, to produce ultimately an optimized system. A functional, user friendly adaptive mirror that works in visible light would bring enormous benefits to all of optical astronomy. It is appropriate that NSO, which has immediate and stringent requirements for high resolution imaging, undertake to provide such a device. Solar research areas that would rapidly advance as a direct outcome of a successful adaptive optical system are:

- Convection. One of the primary modes of energy transport in stars involves compressible, turbulent, three-dimensional flow in a strongly radiating medium. It has proved to be extraordinarily difficult to model. The Sun—the only star on which we can see surface detail—provides an excellent opportunity for developing better theories of convection. Convective motions of sufficiently high frequency can propagate as internal gravity waves. Theory suggests that their wavelengths are less than 1.0 arcsec, that they remain
unresolved in current velocity observations, and that they broaden line profiles. These waves could carry considerable fluxes of non-radiative energy, which may contribute significantly to the heating of the upper atmosphere. Since the causes of photospheric and chromospheric heating remain unidentified, the detection of these waves poses a challenge to solar astronomers.

- Magnetic flux elements. The solar magnetic field is responsible for the structure and dynamics of most of the phenomena visible in the solar atmosphere. Solar magnetic flux appears in the solar atmosphere predominantly (some researchers believe almost exclusively) as subarcsec elements, or flux tubes, with field strengths around a kilogauss. The emergence, transport, equilibrium, coalescence, submergence, and decay of these elementary flux tubes are topics of intense interest in solar physics. Waves along the flux tubes and dissipation by reconnection and anomalous plasma processes must certainly contribute to the heating of the upper solar atmosphere. These higher altitude processes, in turn, are driven by the interaction of strong flux elements and small scale convection in the photosphere. The evolution of sunspots also involves a great variety of flux transport and reconnection processes at the subarcsec level.

- Flare energy release and transport. The storage of energy in active regions and its release and transport during flares involve complex MHD and plasma processes that are only partially understood for lack of sufficient spatial resolution. The release of flare energy is also believed to occur on extremely small scales. Aside from their intrinsic astrophysical interest, solar flares represent an important feature of solar activity. They affect the Earth by disrupting communications, long range power transmission, and manned space flight. Since the initial flare process is predominantly magnetic in character, the same techniques (e.g., subarcsec polarimetry) may be used as for the quiet Sun.

- Small scale dynamics of the chromosphere, prominences, and corona. Magnetic flux tubes, driven by photospheric motions below, drive plasma motions in the upper atmosphere. Observations from space (e.g., SMM, HRTS, rocket flights) have given tantalizing glimpses of the complex behavior of the plasma and fields at these heights, but improved understanding of the physical processes involved requires more regular observations at high spatial resolution.

- High resolution observations in conjunction with space experiments. Space platforms can provide the ultimate in spatial resolution of the Sun. However, observations at the highest possible resolution from space are several years in the future. A well conceived long term program of high resolution solar observations from the ground is an important predecessor for any space program. Ground observations serve to frame incisive questions for space experiments, to develop plasma diagnostic techniques, and to provide the time history of the solar magnetic cycle that is necessary to place the space experiments into proper perspective. Also during the operational period of a high resolution solar space mission, the NSO can play a critical complementary role as was amply demonstrated with SKYLAB, OSO-8, and Solar Maximum Mission (SMM). The NSO intends to play an active role in coordinating ground-based observations during the flight of HRSO, when that opportunity presents itself.
Photoelectric Patrol Coronagraph (PPC). The Emission Line Coronal Photometer, which observes the corona in Fe XIV 5303, Fe X 6374 and Ca XV 5694, has been used for systematic recording of the intensity of the three lines on a synoptic basis for several years. These data are important for solar forecasting (they are used for this purpose by the USAF, NOAA, and the SMM Operations Center) as well as for tracking the coronal emission line intensity through the solar cycle. Extended (full day) observations with the coronal photometer have detected subtle transients in the emission line corona. This discovery indicates the existence of a previously unknown regime of frequent low level coronal activity. To investigate these transient events systematically it is necessary to carry out such extended observations on a regular basis whenever active regions are near the limb and the sky brightness is sufficiently low. For this we need a dedicated coronagraph feed. We therefore will be upgrading the coronal observing systems at Sacramento Peak to provide more continuous, higher signal-to-noise observations of coronal activity, including mass ejections, oscillations, and other targets of opportunity, than has been possible before. This will be accomplished by recommissioning the spare coronagraph on the Evans Solar Facility spar as a dedicated feed for the Coronal Photometer.

Flare photometer upgrade. Five years of operation of the multi-band polarimeter at the Hilltop facility at Sacramento Peak have yielded several superb examples of the time development of white light flares, which are among the most impulsive and energetic of solar flares. It has become evident from a detailed analysis that simultaneous recording of several wavelengths is desirable. Therefore, the present system, which uses six spectral bands each recorded on separate exposures, will be replaced by redesigning the existing "Quad" telescope on the Hilltop spar. The number of wavelengths recorded simultaneously will be reduced to four, but will include a new one in the near infrared at approximately $\lambda$ 7500 to improve overall precision of the analysis.

Infrared instrumentation. One of the more promising avenues of research in solar physics in the next several years is likely to be the solar infrared. The recent discovery at NSO of numerous atomic emission lines near 12 $\mu$m opens many exciting possibilities. The all reflecting optics of the McMath telescope provide high transmission at all wavelengths accessible to ground-based observation and so are well suited to infrared solar astronomy. The diffraction limit of the 1.5-m McMath Telescope is less than 2.0 arcsec at 10 $\mu$m. Its large collecting area is vital for spectroscopic observations in the infrared: the number of photons per Doppler linewidth is some twenty times smaller at 10 $\mu$m than at 0.5 $\mu$m.

The McMath complex already offers two powerful auxiliary instruments for infrared work: the 1-m FTS and the Infrared Spectrograph (IRS).

The FTS has a unique combination of spectral resolving power (typically $R \sim 500,000$), total spectral range (0.3 - 20 $\mu$m) simultaneous spectral coverage (up to a factor of four in wavelength), wavelength accuracy (vacuum wavenumbers to better than one part in $10^3$), and freedom from scattered light. For solar observations, signal-to-noise ratios in excess of 1,000 are routinely obtained.

The IRS was designed exclusively for infrared work. Its high reflectivity, double pass design, combined with one of the world's largest spectroscopic gratings, provides efficiency, good spectral resolution ($R \sim 250,000$), and the flexibility to accommodate a variety of detectors and observing techniques.
The capabilities of the FTS and the IRS are complementary: the FTS for spectral coverage, precise wavelengths, and the detailed analysis of line profiles; the IRS for spatial resolution and the ability to accept large array detectors.

To realize the full potential of the McMath Telescope for infrared astronomy it must, during the next ten years, be mated to modern infrared detector packages and data systems. What follows is a schematic list of needed auxiliary instrumentation and some of the scientific capabilities it will provide.

- **1 - 5 μm camera.** A derivative of an existing NOAO camera, incorporating a 58 x 62 InSb array, this instrument will provide three new capabilities: (1) spectropolarimetry of Fe I 1.565 μm for maps of longitudinal field strength (other candidate lines include Na I 2.208 μm and, in sunspots, Ti I 2.231 μm); (2) direct imaging in the 1.63 μm and 3.70 μm continuum windows, reaching from 40 km below to 40 km above the base of the photosphere; (3) area spectroscopy of the CO fundamental vibration-rotation bands near 4.67 μm to infer the lateral temperature structure of the temperature minimum region.

- **5 - 25 μm camera.** This instrument is a further derivative of the 1 - 5 μm camera (which is already designed for helium as well as nitrogen cooling), incorporating a silicon Block Impurity Band (BIB) array, 20 x 60 or larger (10 x 50 devices of this type are already taking astronomical data). It will provide: (1) area spectroscopy and spectropolarimetry of the 12 μm lines, for analysis of magnetic fluxtubes; and (2) direct imaging in the 11 μm continuum window, probing 130 km above the base of the photosphere.

- **Cooled spectral isolators.** Beyond 2.5 μm, thermal background radiation becomes important relative to the solar flux. For high resolution spectroscopy it is important that only a rather narrow bandpass reach the detector (R ≥ 1000) so that undispersed background light does not overwhelm the dispersed solar signal; similar considerations apply to Fourier transform spectrometry. The spectral isolator must itself be cool, and it must be an integral part of the detector package or mated to it without intervening warm surfaces. Depending on the application a grating-spectrometer postdisperser, tunable Fabry-Perot filter, or sets of narrowband interference filters, might be preferred.

- **Data systems with real time processing.** In typical solar applications low noise infrared arrays will be saturated in a fraction of a second. To build up the signal-to-noise ratios that will often be required, it will be necessary to analyze tens or hundreds of frames of data at each spectral/spatial location. The only practical way to accomplish this is by correcting for instrumental effects and averaging frames before writing a much smaller amount of data to secondary storage. The problem of "data glut" is a new (and gratefully received) problem for most infrared astronomers, but solar astronomers have faced and solved similar data problems in devices such as the Kitt Peak 512-channel magnetograph and in designs for the new Kitt Peak spectromagnetograph and the CHIRP system at the Sacramento Peak Vacuum Tower Telescope.

- **Infrared adaptive optics.** The advantages for adaptive optical systems of observing in the infrared have been described elsewhere in this plan. Coupled to an adaptive mirror similar to the prototype now being tested by NOAO's Advanced Development Program, the McMath Telescope is capable of
0.25 arcsec resolution at 1.65 \( \mu \text{m} \). As one example, the combination of this spatial resolution (180 km on the Sun) with the diagnostic power of the Fe I 1.565 \( \mu \text{m} \) line has extraordinary potential for the study of solar magnetic fields.

Other projects. Other short and long term projects are planned requiring optical, mechanical, and electronic resources to develop small instruments as well as numerous instrumental upgrades. A major project in a late definition stage is to reconfigure the instrumentation of the Vacuum Tower Telescope to optimize its use in conjunction with "fast mirrors" (image motion correction) and adaptive optics. As well, a new spectrograph will be designed to match its spectral resolution optimally with CCD detectors and to allow simultaneous recording of spectra and associated spectral images.

E. Advanced Development Program

The role of ADP.

In astronomy, the perennial quest is for several things: larger light collecting area, higher angular resolution, broader wavelength coverage, and greater system throughput. This quest sets the goals of the ADP. The heart of our program is to design and build a 16-m National New Technology Telescope (NNTT), two or more 8-m telescopes as precursors to the NNTT, and a distributed array of interferometric telescopes. Providing for the best use of the largest telescopes is what determines the balance of our program.

Building 8-m telescopes and the NNTT, which incorporates four 8-m mirrors that will work together as a unit, demands a range of technological advances. Some major ones are the casting of 8-m mirror blanks, figuring and supporting 8-m mirrors for 0.25 arcsec imaging, arranging for four mirrors to work in concert, and building auxiliary instruments for a very large beam. These challenges are described in Chapter III.

The distributed array will take form initially as an interferometric test facility with three to five 0.5-m telescopes linked via delay lines to a central station. With its long baseline (up to 100 meters), this unfilled array will nicely complement the imaging and spectroscopy done with the NNTT. The distributed array is described further in Chapter III.

Full advantage cannot be taken of 8-m and 16-m telescopes without certain other developments. To achieve the full interferometric resolution capability of the NNTT at visible wavelengths, we need refined image reconstruction algorithms. If distributed arrays and the large telescopes are to advance infrared imaging, we must have good IR array detectors, IR adaptive optics, single-mode fibers as waveguides and radiation mixers, and interferometric imaging techniques. The spectrographs on 8-m and 16-m telescopes will need very large gratings and efficient multi-mode optical fibers. All of these areas also are covered by ADP research. The Advanced Development Program will benefit not only NOAO projects and telescopes but also other existing and planned telescopes.

The current ADP program.

The ADP program (aside from the work directly related to the very large
telescopes and the distributed arrays, described in Chapter III) centers on ways to achieve higher angular resolution and broader wavelength coverage.

**Astronomical site evaluation.** Between 1984 and 1986 the ADP carried out a site study, together with the U. of Arizona, the Smithsonian Astrophysical Observatory, and the U. of Hawaii. The prime site characteristics tested were seeing and infrared atmospheric emissivity. Other characteristics monitored were near ground turbulence, wind velocity, and temperature gradient.

Two sites were tested: Mt. Graham in Arizona and Mauna Kea in Hawaii. Both were known to be relatively clear and dark, and both are over 10,000 feet high, reaching above a large percentage of the IR-absorbing water vapor in the atmosphere.

Based on this site survey, Mauna Kea was chosen as the site for the NNTT. The root mean square (RMS) image motion on Mauna Kea was found to be surprisingly low--0.2 to 0.3 arcsec at the 50th percentile. This means that the 0.25 arcsec goal for imaging with large telescopes is consistent with what the atmosphere can deliver. In addition, the latitude and climate of Mauna Kea allow good study of the center of the Milky Way (and associated objects), which transits at an elevation of 41° at midnight in June.

Further studies of the site on Mauna Kea will characterize it for design of telescopes, enclosures, and instrumentation. Of particular interest are: (1) a determination of the image size that can be achieved with large telescopes; (2) an understanding of why telescopes on Mauna Kea do not yet routinely achieve the image quality measured during the site survey; (3) measurements of speckle lifetime and isoplanatic patch size (atmospheric stability and uniformity); and (4) measurement of the IR sky noise characteristics, which will affect the planning of IR instrumentation.

**Sharpening of telescope images.** The quality of telescopes is measured by how much light they can gather and in how small an image they can deposit this light. Sharper images allow the astronomer to resolve the important details on the object under study--details that are often needed to identify the physical processes that are acting. Sharper images also improve our ability to detect compact point sources against the ever present sky background. They allow the use of narrower slits in spectrographs, thus improving spectral resolution. One of the prime justifications for the Hubble Space Telescope is its ability to obtain small stellar images (0.1 arcsec) by placing the telescope above the Earth's turbulent, image disturbing atmosphere. Putting large telescopes in space is, however, very expensive (> $1B for the 2.4-m HST). NOAO's program is aimed at sharpening the images in existing telescopes as well as in future large ground-based telescopes.

In collaboration with the U. of Hawaii, NOAO is continuing a detailed study of the optical properties of the atmosphere above Mauna Kea. Thorough understanding is essential for the design and implementation of image sharpening techniques, especially of adaptive optics. In adaptive optics the wavefront disturbances of the atmosphere and of the telescope are measured with very high speed and immediately corrected by means of a so-called adaptive mirror (or "rubber mirror"). Since both the required wavefront correction rate and the number of required corrections increase rapidly as the imaging wavelength decreases, the correction of astronomical images at infrared wavelengths above 2.0 μm allows the use of fainter wavefront reference stars than would be necessary for visual image correction system. In
addition, at the longer infrared wavelengths, the applied corrections are useful over a larger region of the sky about the reference star. NOAO is therefore implementing a prototype adaptive optics system for wavelengths above 2.0 μm to be used at the 4-m Mayall Telescope at Kitt Peak. There it is expected to give an image quality comparable to the image quality of the HST (0.1 arcsec). This prototype system will be used to gain experience with adaptive optics, to enhance the research capacity of the national telescopes, and to aid in design of adaptive optics systems for 8-m and 16-m telescopes. In these larger telescopes the gain in angular resolution (2 and 6 times) will make the adaptive optics truly outstanding.

At shorter, visible wavelengths the possibility of using adaptive optics is opened up by the potential availability of artificial stars produced by the reflection of a laser beam by the atmosphere, a technique being pioneered in France and at the U. of Illinois. However, adaptive mirrors for 8-m telescopes at visible wavelengths need many elements (~1600), all of which must be adjusted very rapidly (5 millisec). Those mirrors are not now available to astronomy. The NOAO’s Advanced Development Program is currently engaged in the development of bimorph adaptive mirrors. These mirrors are formed on a sandwich of two piezoelectric wafers. By means of a set of electrodes on the wafer surfaces, the local surface curvature can be controlled to produce the desired surface shape. Such devices are expected to provide low cost adaptive mirrors with the large number of elements required for visual image correction. We intend to collaborate with the U. of Illinois to pursue this exciting technology and its implementation. If it is successful ground-based telescopes will do as well as telescopes of comparable size in space, both in light gathering power and in image sharpness. Some of the techniques developed for adaptive optics within NSO are relevant to nighttime astronomy, and the ADP and NSO programs are coordinated.

Interferometric imaging. Adaptive optics will eventually provide the means to sharpen telescope images to the diffraction limit of the telescope. This should be possible in the near future at infrared wavelengths. However, diffraction limited imaging at optical wavelengths will require the development of complex sensor and adaptive mirror technology as well as a successful artificial star program. Adaptive restoration of visible images is therefore not likely to be available soon.

To reach the optical diffraction limit without delay, the ADP is aggressively pursuing a program in interferometric imaging using both image-plane and pupil-plane interferometry. By means of a detailed analysis of the recorded image distorted by the atmosphere, using state of the art mathematical algorithms, the undistorted image of the object is recovered. These techniques are used to recover the images from pupil-plane and image-plane interferograms in single aperture (and NTTT-type) telescopes. But in addition, interferometric imaging techniques are also directly applicable to the observations made with distributed arrays. Their usefulness will therefore persist well beyond the date at which adaptive optics is implemented on single aperture telescopes. This field of research is developing rapidly, as is evident from the very successful joint workshops and conferences on this topic organized by ESO and NOAO.

Image-plane interferometry is also referred to as speckle interferometry. Major recent advances in power spectrum and bi-spectrum analysis of the speckle images of astronomical objects have resulted in accurate estimates of both the amplitudes and the phases of the Fourier components of their undistorted images. The resulting images compare very favorably with images restored with other techniques like the well known Knox-Thompson technique. As part of this program we have
constructed a speckle camera for infrared wavelengths (1.5 - 5.0 μm), which will be used at the KPNO 4-m telescope with the SBRC array imager. Initial observations will be of young stellar objects, star formation regions, solar system objects, and stars with large mass loss. The mathematical algorithms developed as a result of our work on image-plane interferometric imaging will become an integral part of this user qualified IR interferometric imaging camera.

Interferometric imaging in the pupil-plane, common in radio astronomy arrays, is receiving increasing attention in optical astronomy. For bright sources it can be shown that an image reconstructed with pupil-plane interferometry will have a better signal-to-noise ratio than with image-plane interferometry. ADP scientists are comparing the two forms of interferometric imaging in detail, while also examining the potential of combining both. Both forms could be used together to determine, for example, the amplitudes by pupil-plane interferometry and the phases by bi-spectrum (triple correlation) analysis in the image plane. Another ADP project is an experiment with dual rotational shear interferometry observations in the pupil-plane, to determine phases by direct phase closure techniques.

Single mode optical fibers. In the planning of large distributed arrays, a key question is how to gather the light collected by several telescopes, and combine it in such a way that the beams from all the telescopes are in phase. This is required to achieve the high angular resolution corresponding to the wide separation of the telescopes. In radio astronomy this has long been done with waveguides and coaxial cables that carry only a single mode of electromagnetic radiation. One possibility for optical telescope arrays is the optical analog of a radio waveguide.

A single mode (SM) optical fiber is such an analog. A multi-mode fiber (such as the kind used in multi-object spectrographs) will not do, as the various modes (or wavefront shapes) will propagate at different speeds and therefore be detected out of phase with each other. SM fibers have only recently become commercially available, and part of the ADP program is to test them in the laboratory. The question is, can SM fibers provide a simple means of combining the light collected by several small apertures in a long baseline, wide bandwidth interferometer?

So far the laboratory results are encouraging. Phase drift, noise, and polarization fluctuations can be made insignificant compared to the atmospheric noise in a ground-based system. Specific steps can be taken to optimize the performance of SM fibers: length differences can be accurately measured and compensated for; the fibers can be installed underground to reduce thermal effects; bending can be minimized or corrected for; and highly birefringent fibers can be used to overcome polarization nonuniformities. Theoretical studies have shown that a single fiber can transmit a wide bandwidth (0.6 - 1.0 μm) over 1-km baselines.

SM optical fibers offer certain advantages over conventional mirror systems in interferometers:

- They replace and simplify the alignment optics.
- They equalize the optical paths from the telescopes to the laboratory. (Delay lines are still needed, however, to compensate for the path differences from the source to the telescopes.)
- They make the optical system easily expandable.
• They could be used in a space-borne interferometer to simplify the optics.

NOAO's current work has demonstrated in the laboratory that high contrast, accurate visibility measurements can be obtained in a long baseline interferometer with fibers in each arm. Future work will concentrate on optimizing the signal-to-noise ratio in fiber coupled interferometry. This will include studies of the optical effects of vibrations and temperature changes, the efficiency of fibers as a function of pupil diameter and seeing conditions, and the signal-to-noise ratio of the fiber interferometer compared to conventional interferometers.

F. Computer Support

Computer support at the NOAO is an essential element of the Observatories operations. Computers are not only intensively used in the acquisition, reduction, and analysis of astronomical data, but they are involved in the design and development of new telescopes and instruments, in innovative data and image restoration techniques, and in the production of scientific papers that present the final results. Computing facilities at the NOAO will have to meet the growing demand from a nationwide community of users for rapid processing of their data, for access to data banks from remote sites, and for the development of increasingly sophisticated hardware and software to allow more complex data analysis procedures. This demand, together with the prospect of very large format detector arrays and the possibility of additional observing facilities, will require the NOAO to maintain a complex and state of the art computing capability.

Computing activity at NOAO takes place at the individual sites and at the Tucson headquarters. Computing facilities which are specific to the various observing locations are described in the sections devoted to discussing the individual sites; the material presented here covers computing activities which are observatory wide or which involve more than one site.

IRAF.

The Image Reduction and Analysis Facility (IRAF) is a general purpose software system for the reduction and analysis of scientific data. The IRAF system provides programs for general image processing and graphics applications, plus a large selection of programs for the reduction and analysis of optical astronomy data. The system also provides a complete modern scientific programming environment, making it straightforward for institutions using IRAF to add their own software to the system. Every effort has been made to make the system as portable and device independent as possible, so that the system may be used on a wide variety of host computers and operating systems with a wide variety of graphics and image display devices.

The major components of the IRAF system are: (1) the command language which is the user's interface to IRAF; (2) the applications programs which consist of the system utilities and the scientific applications programs; (3) the virtual operating system which is the basis for the command language and the applications programs; and (4) the kernel which communicates with the host system. All software except the kernel is completely portable to any IRAF host.

The IRAF project began in the fall of 1981 at KPNO (NOAO did not yet exist at that time), and the initial version was developed under UNIX. The Space Telescope
Science Institute (ST ScI) selected IRAF to host their Science Data Analysis System in December 1983 and carried out the initial port of IRAF to VAX/VMS during 1984 and 1985 under a collaborative arrangement with NOAO. NOAO completed the integration of the UNIX and VMS versions of IRAF in late 1985, leading to the first public release of the system in early 1986. NOAO currently supports IRAF in half a dozen or so different configurations on several host systems, with a number of new exports currently in progress. It is available on the latest versions of the VMS, Berkeley UNIX, Ultrix, AOS/VS, and Sun/UNIX operating systems, and it is currently in use at more that 140 sites in the U.S. and around the world.

IRAF is not yet a finished product, since several major software packages are still in prototype and program documentation is incomplete. The rapid acceptance of IRAF under these conditions was possible only because the demand was very great and because IRAF is both easy to learn and very powerful. Discussions with users at NOAO and at other institutions indicates that use of IRAF for data reduction, and as an environment for software development, will expand rapidly. Within three to five years we project that IRAF will be in operation at close to 500 sites, not including individual use on workstation class personal computers.

NOAO distributes IRAF with regular updates, including several thousand pages of documentation, and offers telephone and electronic mail support for installation and use of the software. NOAO distributes an IRAF newsletter and responds to bug reports and requests for software improvements. While the expense of supporting IRAF is not negligible, we find that providing software which can be taken home with the data generates large returns in the productivity and expertise of the observatory clientele, and reduces the demand on NOAO computing resources.

The ST ScI decided in 1983 to run SDAS with the IRAF command language. More recently, the decision has been taken at ST ScI to code SDAS within the IRAF virtual operating system. This means that all NOAO and ST ScI science analysis software will be within a single, homogeneous system, minimizing redundant development, and providing scientists with a single data reduction environment. Several institutions have initiated major software development within IRAF, and others plan to do so.

The success of IRAF and its acceptance by the astronomical community are severely taxing the resources available to NOAO. Systems software development, applications programming, documentation, response to outside requests, and all other IRAF related activities are carried out by a group of only six individuals. As the use of IRAF continues to grow the demands placed on this group will increase. The IRAF effort will require more resources if it is to realize the promise shown to date.

Facility improvements.

Computing capacity. The present and anticipated demands described at the beginning of this section will not only require an increase in the computing capacity at NOAO but also a change in the way this capacity is realized. In the past, most scientific computing has been done at a central facility with one or more medium to large computers linked to users via remote terminals. Technical advances are making possible ever more powerful computers at lower prices and smaller physical dimensions. This is leading more and more to the practical use of workstations to carry out a major portion of the computing needs. Workstations are now in use at many of the telescopes, and more are planned. These allow most of the data reduction, and a significant amount of the analysis, to be done by the observer on
the mountain. The workstations, all of which run IRAF, are also being installed at
the central facilities in La Serena and Tucson, and we expect to acquire more of
these devices in the future. The high quality image display, large computing
capacity, and small size of these workstations make them ideal for the sophisticated
and interactive data analysis possible with IRAF. Their declining cost and increasing
performance will soon allow NOAO staff and visitors the immediate and sometimes
exclusive access to powerful computing capacity that is required to analyze data
from complex instruments.

Although workstations will become more numerous and will replace some of the
smaller and less effective computers, NOAO plans to retain high speed, general
purpose computing capacity. This is needed for general scientific computing and
theoretical modelling, but it will also be required for some advanced data processing
and observing techniques which are being developed and which require large
amounts of computing capacity. Two examples are image enhancement programs and
speckle interferometry. Maintaining this computational ability will be done in two
ways. In house capacity will be available through advanced machines such as the
DEC 8600 and its replacement, possibly a vector/multiprocessor machine similar to
the "mini-supercomputers" now being developed. Remote access to true
supercomputer capacity will be maintained through the NOAO high speed link to the
San Diego Supercomputer Center. This facility, through its planned upgrades,
provides access to state of the art supercomputer capability together with the
peripheral support available at a national computing center. The supercomputer is
being used for data analysis, image enhancement, telescope design, and theoretical
calculations.

Data archiving. Advances in detectors and instrumentation indicate that the
amount of digital data being placed in permanent storage at NOAO may increase by
more than a factor of ten in the next few years. Storage on magnetic media is not
satisfactory because of the large volume required, and the evolution of optical
storage techniques is being closely followed. Implementing an effective archiving
program will involve a significant amount of effort and resources; NOAO plans to
continue to develop specifications for storage media and investigate archiving
techniques during the next few years.

G. Global Oscillation Network Group

The Global Oscillation Network Group (GONG) is carrying out an international
project to study the internal structure and dynamics of the closest star by
measuring resonating waves that penetrate throughout the solar interior—a
technique coming to be known as helioseismology. To overcome the limitations of
current observations imposed by the day-night cycle at a single observatory, GONG
is developing a six-station network of extremely sensitive and stable solar velocity
mappers located around the Earth to obtain nearly continuous observations of the
"five-minute" oscillations, as well as direct measurements of the "steady" motions of
the solar surface itself. To accomplish its objectives, GONG is also establishing a
distributed data reduction and analysis system to facilitate a coordinated analysis of
these data. The primary analysis will be carried out by a dozen or so teams, each
focusing on a specific category or problem. Membership in these teams is open to
all qualified researchers; 92 responses, representing 50 different institutions, have
been received to an initial "Invitation to Participate." NOAO is carrying out the
GONG project in close collaboration with the community.
Historical perspective.

In the early 1980s, the flow of exciting new results demonstrated the growing number of crucial questions that helioseismology could address; e.g. stellar internal rotation and oblateness, the neutrino deficit, the efficiency of convection. At the same time, the limitations of observations from a single site, or from the relatively brief campaigns at the South Pole, were becoming more and more apparent, and pressure to achieve long, continuous observations was mounting. In April 1984, NOAO sponsored a workshop to explore the scientific questions, and to investigate the technical issues. As a result of the interest and support manifested at the workshop, NOAO staff, in collaboration with the scientific community, established the GONG to coordinate efforts towards the design, construction, and utilization of a network of stations, distributed in longitude and dedicated to obtaining a uniform set of data. A proposal was generated and submitted to the NSF in late 1984, by the NOAO on behalf of the entire scientific community.

In FY 1985, an examination of worldwide climatic data was undertaken to identify potential sites. Simulations that allowed for equipment failures and weather history from suitably located observatories indicated that a minimum of six sites, spaced roughly equally in longitude, would be required to achieve the design objective—a minimum of three years of nearly unbroken data. A robust, automated, digital sunshine monitor for a survey of candidate sites was developed. Alternative technologies for making the solar velocity measurements of the requisite precision were investigated and the nature of the overall investigation began to take shape.

In FY 1986 an interim technology development program led to the design of a variable path length Michelson interferometer, with a narrow prefilter isolating a single solar line, to provide an ultra-stable, and ultra-sensitive velocity measurement. Early in the year the site survey started operation at 10 locations: Arizona Western College (Yuma), Big Bear Solar Observatory of the California Institute of Technology, the Institute for Astronomy of the U. of Hawaii sites at Haleakala and Mauna Kea, the Australian Ionospheric Prediction Service’s Learmonth Solar Observatory, the Udaipur Solar Observatory (India), the Instituto de Astrofisica de Canarias site at Izaña (Canary Islands), and the Las Campanas and the Cerro Tololo Inter-American Observatories (Chile).

The project obtained a go ahead from the NSF in FY 1987 and is directed toward completion of a prototype instrument in FY 1988. The breadboard instrument is under test, and elements of the prototype are beginning to take shape. Meanwhile, preliminary results from the site survey have validated the concept of a network, and indicate that we may anticipate observing duty cycles well in excess of 90 percent. The site survey will continue, with a selection of the final sites planned for 1989.

The instrument.

The five-minute oscillation is a subtle effect. Individual modes exhibit velocities of less than 20 cm/s, while the sum of all the modes is only a few hundred m/s. The ultimate intention is to have the measurements be limited by the Sun’s "random" surface motions. This means developing six stable instruments capable of making imaged velocity measurements with a precision of significantly less than 1.0 m/s.

The basic idea is to separate a single solar absorption line and determine its precise (Doppler shifted) wavelength. The instrument chosen for this task is called a
Fourier Tachometer, similar to the one developed in collaboration with the High Altitude Observatory, and which is currently in routine operation in Tucson. Based on the Michelson interferometer, it processes the light from all parts of the solar disk simultaneously to produce a velocity sensitive image of the Sun. This is picked up by a 256 x 256 pixel solid state detector and stored in the data acquisition computer’s memory.

At the conclusion of each 60 to 75 second acquisition cycle, the computer reads the memory and derives the line-of-sight velocity for each individual pixel. Actually, three intensity images, differing in phase by 120° are summed, differenced, and divided to produce a single velocity image, as well as an intensity and a line strength image. The resulting velocity image is then stored on a magnetic tape cartridge, along with an intensity image and other information, for subsequent reduction at the central data reduction and analysis facility.

The entire field instrument will reside in an environmentally controlled shelter building which houses the "light-feed" (it’s so small we can hardly call it a telescope), Fourier Tachometer, control and acquisition computers, and data tape recording equipment.

The light-feed itself will be a fully automatic system which will turn itself on each day, locate and track the Sun, continue to track using an ephemeris during cloudy periods, and supervise and report its environment and operational status. Adaptive software is being developed which will even create a real world ephemeris for the actual site and conditions, as deviations from the "pre-canned" ephemeris are noted.

Data management and analysis.

Even at first glance it is clear that the real challenge in the areas of GONG data reduction and analysis are presented by two factors: (1) a monumental volume of data; and (2) a long sequence of complex computing tasks. Each station in the network will produce at least 200 megabytes of data every day. The whole network will generate a gigabyte a day, seven days a week, for three years. Over this time the total accumulation of field data will exceed one terabyte! The reduction process itself is not trivial. Each individual 64K pixel frame of each station must be adjusted, pixel by pixel, for a variety of instrumental, photometric, and geometric effects. Furthermore, the Doppler effect of the known motions of the Earth and the Sun also must be removed. As many as three adjacent GONG stations may observe simultaneously for periods of several hours. These data must be merged into a single stream of the best frames attainable at each moment.

Once these preliminary tasks are complete several more computationally intensive reductions will be performed. For example, the decomposition of the image data into time series of spherical harmonic coefficients, and their subsequent reduction to frequency spectra will be standard processes. Finally, the raw field data, the ultimate reduced data sets, and several intermediate stages must all be placed in long term storage in computer based archives using a combination of optical disks and rotary head tapes. Scientific analysis of the data will generally proceed from these archived data sets.

While researchers may choose to write their own specific analysis programs, the GONG project and its scientific teams are establishing a central users’ library of contributed analysis software which will be available for general use. This library
will include the data access and display system as well as basic analysis tools which will be fully supported and highly transportable, so researchers can pursue work from their home institutions, if they wish.

The central GONG computing facility will feature a main computer in the "super-mini" to "mini-super" class. In addition to performing routine data reduction tasks, this system will also be available for research by both on-site visitors and by remote access.

Current status and future directions.

The development of the field instrument is underway, and this will lead to a complete prototype field system in the fall of 1988. Following the validation of this system fabrication of the six actual field systems should begin. Unfortunately, no funds are available in FY 1988 to purchase the necessary components, and the completion of the GONG project will be delayed by one year. Installation of these units at the six sites is scheduled for 1991, with full network operation to begin late in 1991.

TABLE VIII

GONG MILESTONES

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<thead>
<tr>
<th>Month</th>
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<td>First Community Workshop</td>
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<tr>
<td>September 1984</td>
<td>Project Proposal Submitted to NSF</td>
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<tr>
<td>October 1985</td>
<td>Interim Technology Development</td>
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<tr>
<td>October 1986</td>
<td>Project Start</td>
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<tr>
<td>November 1986</td>
<td>Full Site Survey Network Operational</td>
</tr>
<tr>
<td>January 1987</td>
<td>Begin Integrated Light Tests - Doppler Imager Breadboard</td>
</tr>
<tr>
<td>August 1987</td>
<td>Begin Imaged Testing - Doppler Imager Breadboard</td>
</tr>
<tr>
<td>July 1988</td>
<td>Doppler Analyzer Design Review</td>
</tr>
<tr>
<td>November 1988</td>
<td>First Light Full Prototype System</td>
</tr>
<tr>
<td>January 1989</td>
<td>System Design Review</td>
</tr>
<tr>
<td>March 1990</td>
<td>Site Selection Completed</td>
</tr>
<tr>
<td>April 1990</td>
<td>Begin Integration of Field System Components</td>
</tr>
<tr>
<td>October 1990</td>
<td>Data Reduction and Analysis Hardware Ordered</td>
</tr>
<tr>
<td>March 1991</td>
<td>Data Reduction and Analysis Center Operational</td>
</tr>
<tr>
<td>April 1991</td>
<td>Begin Site Installation</td>
</tr>
<tr>
<td>October 1991</td>
<td>Network Operational</td>
</tr>
<tr>
<td>September 1994</td>
<td>Data Acquisition Completed</td>
</tr>
<tr>
<td>September 1995</td>
<td>Initial Data Analysis Completed</td>
</tr>
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</table>

The data reduction and analysis system is a major component of the program and is being developed concurrently. Even before the installation of the network, data acquired during the validation of the prototype should provide the basis for important research. The design and construction of the needed software tools will require the efforts of both the project staff and many other members of the solar physics community. The principle hardware for this system will be procured and installed in early 1991 and will be in full operation later that year.
Coordination with the scientific community continues to be assured by regular consultation with a five member Scientific Advisory Committee, a quarterly newsletter, and an annual GONG meeting (with over 60 participants from nearly 40 institutions and 15 countries in 1988). The science teams have already stimulated four topical workshops: on "Solar Interior Models" held at Yale, "Solar Inverse Problem" held at the Harvard Smithsonian Center for Astrophysics; "Supercomputers Usage" held at the U. of Illinois; and "Artificial Data" held in Tucson, with additional meetings planned in 1988.

The GONG project is slated to gather data for a minimum of three years. Full scale data analysis activities will continue for at least one year beyond the end of the data gathering phase. If the results of these studies indicate a need, the continuation of data gathering for a longer fraction of the solar cycle remains a possibility. In any case, beginning in the early 1990s we can look forward to some truly exciting developments in our understanding of our nearest star.

H. Future Telescope Technology (FTT)

Rapid improvements in detector technology in the past decade have made it possible to make major advances in observational astronomy using existing telescopes. Large CCDs now provide imaging with nearly 100 percent quantum efficiency; imaging photon counting detectors locate individual photon arrivals with both spatial and temporal precision; recently we have witnessed even more remarkable advances in detector capability at infrared wavelengths, with the implementation of sensitive array detectors. Although we expect continuing growth in the size (or number of pixels) of detectors, we have approached the natural limit of their sensitivity (100 percent quantum efficiency). Future gains in observational astronomy will therefore have to come from the construction of telescopes with larger collecting areas and with sharper imaging capability.

The 1990s are likely to see construction of several large, high quality telescopes at universities and at the national observatories, both in the U.S. and abroad. The basic elements of these telescopes are mirrors 8-m in diameter. Together with the rest of the telescope, these mirrors should be capable of giving images of 0.25 arcsec. These 8-m mirrors will be used either in individual telescopes, in compact arrays (as in the 16-m NNTT), or in distributed arrays (as in the 16-m European Very Large Telescope). Both the size and the imaging quality of these mirrors and telescopes will significantly exceed those of existing telescopes. The challenge posed to NOAO's Future Telescope Technology program is to develop the technologies needed to achieve that performance at a cost well below that of conventional telescope technology. Together with the university community, NOAO is aggressively pursuing these technologies. Most of the emphasis is on the production of low cost, large mirrors. With support from NOAO, R. Angel at the U. of Arizona has been developing a facility to spin cast light weight honeycomb borosilicate glass mirror blanks. The U. of Arizona and NOAO are cooperating with potential users of such mirrors and with industry to assure that the needs of the community for large mirrors will be met as cost effectively and as soon as possible. The first 8-m borosilicate blank is expected in early 1991. Parallel with the development of the casting facility, NOAO is developing the techniques needed to convert these mirror blanks into high quality telescope mirrors. The requirement to give 0.25 arcsec images is at least as challenging as the casting of 8-m diameter mirror blanks. It requires an exquisite mirror surface quality that can be kept that way under regular astronomical observing conditions on an outstanding, high altitude astronomical observing site like Mauna Kea.
NOAO, together with the U. of Arizona and other future users of the borosilicate mirror blanks, is therefore engaged in an extensive program aimed at meeting this challenge. NOAO is modifying an existing polishing facility to finish a 3.5-m borosilicate glass blank. NOAO and the U. of Arizona plan to build two polishing facilities for 8-m diameter optics. Two facilities are necessary to provide the capacity to polish the many 8-m mirrors required by the various telescope projects. One polishing facility will use the stressed-lap technology being developed at the U. of Arizona, the other will use the variable-distributed-pressure-lap being developed at NOAO for the 4-m polisher. To achieve and maintain the mirror figure in a telescope it is necessary to support the mirrors precisely in variable orientations with respect to gravity. NOAO is developing support mechanisms for the 3.5-m and 8-m mirrors on the basis of detailed computer analysis. These mechanisms include variable pressure back supports which will allow us to remove large scale surface distortions introduced by a number of effects and which, under operating conditions, provide for a straightforward maintenance of the optical quality. In addition to good support of these large mirrors, there is a requirement to maintain a high degree of thermal uniformity (0.1°C) in the mirror to prevent thermal warping, and a requirement to maintain the mirror temperature at air temperature to prevent thermally driven turbulence from distorting the star images. The joint NOAO-U. of Arizona program will address these stringent thermal control demands as well. At this point in the FTT program it appears likely that the 0.25 arcsec imaging requirements will be met, notwithstanding the major technological hurdles which still lie ahead of us.

An 8-m telescope with 0.25 arcsec images will be a major advance over the best existing 4-m to 5-m telescopes which give 0.5 to 1.0 arcsec imaging. Yet such a superb device is still far from diffraction limited because of atmospheric turbulence. NOAO is therefore pursuing a program in adaptive optics aimed at removing these atmospheric and residual telescope effects and thus giving diffraction limited images. At a wavelength of 2.0 μm (near infrared), the diffraction limited image quality would be 0.05 arcsec. The image quality would proportionally improve with decreasing wavelength. Adaptive optics gives its biggest payoff for large telescopes where the diffraction limited images are smallest. It is therefore an important component of the FTT program. A prototype of the FTT adaptive optics system is now being assembled for checkout and astronomical use on the 1.5-m McMath and 4-m Mayall Telescopes on Kitt Peak. Following that, we plan to design and build the optics needed for an 8-m telescope and to collaborate with the U. of Illinois to test the feasibility of using artificial stars to measure atmospheric wavefront distortions.

Large mirrors and adaptive optics are the major components of the FTT program. There are other elements of the program like the production of good secondary mirrors, large gratings, high reflectivity coatings, and so on, which play an important though lesser role. NOAO and our collaborators in the university community see the Future Telescope Technology program as the path to a new age of very high technology, sophisticated optical observational astronomy. A proposal detailing the various components of the FTT program through the casting of the first 8-m mirror is being prepared for submission to the NSF.
I. Facilities

Facilities maintenance.

Much maintenance has been deferred during the past few years, and additional needs have arisen as facilities aged. As a consequence, there is a long backlog of projects. The FY 1988 program plan is the first in several years to contain funds budgeted specifically for high priority facilities maintenance items. The most visible evidence of deferred maintenance is the peeling paint on the McMath Solar Telescope at Kitt Peak, but of more concern is the condition of the physical plant at Sacramento Peak. There we will reroof and repaint the machine and electronics shop building; replace water and gas lines (there have been six major leaks in the water lines and two in the propane lines); repaint the main lab, Vacuum Tower Telescope building, and the facilities maintenance buildings; replace boilers; and resurface roads. At Kitt Peak, we will resurface roads and repaint the 4-m building in about three years. At CTIO we will replace a transformer that contains PCBs and improve the electrical, gas, and plumbing networks at the guest house and office in Santiago.

All sites need to replace heavy equipment (bulldozers, snowplows, trucks, front loaders) much of which is more than 25 years old.

Based on the existing backlog of work and on the historical records of expenditures for emergency repairs of storm damage and other major failures of equipment, we estimate that approximately $500K should be budgeted during the first two years covered by this plan and $400K each subsequent year for facilities maintenance and replacement of heavy equipment.

Facilities construction.

NOAO Headquarters—Tucson. The need for additional space in the NOAO Tucson Headquarters has become critical. The GONG project requires about 7,000 square feet to house its staff and computer systems beginning in FY 1990, with smaller amounts of space required before then as the staff ramps up. The analysis and distribution of data is essential to the success of the GONG project, and the need for a data center will continue for several years after observations have been completed. The scope of this effort is not trivial. In addition to the mainframes and peripherals, the GONG Data Management and Analysis Center will have of the order of 10 Gigabytes of hard disk and must provide ready access to a data archive containing 1,800 tapes, 500 optical disks, and 2 "juke boxes" to handle the online portion of the archive. In total, it will be necessary to store five terabytes of data. No funds were included in the GONG proposal itself to provide space for this center.

Space is also required to accommodate increased computer facilities, storage of magnetic tapes and photographic plates—including new Sky Survey plates, and the growing library. If NOAO undertakes the construction of telescopes, then the added staff will require laboratory, shop, and work space.

To provide the required space NOAO proposes to construct a two floor addition onto the East Wing of the building. The East Wing was designed to accommodate a total of five floors plus a basement. This project would provide an additional 21,000 square feet of net space at an estimated cost of $4.0M in FY 1987 dollars.
Cerro Tololo. The 23-mile unpaved road between Tololo and the public highway needs to be improved. It remains dangerous for drivers unfamiliar with its curves and steep dropoffs; we propose to install guard rails for the most critical ten miles of the road.

Since 1963 the generators, warehouse, garage, and several shops on Tololo have been housed in "temporary" buildings of structural steel covered only with corrugated zinc sheeting. The buildings are not designed for mountain weather conditions, and have deteriorated with age. We will replace these buildings during the period of this plan.

Sacramento Peak. In addition to the program to catch up with deferred maintenance, an extension to the main lab is required to provide adequate room for data reduction equipment. Another building to provide weather tight storage for furniture, equipment, supplies, and a covered parking area for observatory vehicles are also planned.

Kitt Peak. Plans for Kitt Peak include an early warning fire detection system for all buildings on Kitt Peak; a water well and pumping stations to provide a source of potable water to supplement the inadequate system for collecting rainfall and snow melt; and additions to the Kitt Peak Visitor Center, including an auditorium, to handle the very large increase in public visitors (we hope to fund a major portion of the Visitor Center expansion with private donations).
V. BUDGET

A. Recent History

In this Chapter we present detailed cost estimates for the programs outlined in this long range plan. In order to understand the issues that shaped the development of the budget, it is useful to consider the funding history of the ground-based observatories now operated by NOAO.

For FY 1988, funding for the NOAO observatories, excluding GONG and the FTT program, will be at the lowest level since FY 1964, the year that the 2.1-m telescope was completed at KPNO. In purchasing power we have a budget for operations and maintenance that is only 10 percent higher than before the inauguration of CTIO, before the construction of the two 4-m telescopes, before the addition of Sacramento Peak to the AURA managed observatories, before the time that sophisticated computers and complex electronic detector systems became essential for every telescope. Apart from FY 1982, staffing is now at the lowest level since FY 1972, the year before the KPNO 4-m Mayall Telescope was dedicated, before first light at the CTIO 4-m, before the addition of Sacramento Peak and the Solar Vacuum Telescope on Kitt Peak.

New funds received from the NSF have been static at a level within $200K of $22.8M uncorrected for inflation, for the four fiscal years 1985 - 1988. This year alone in order to accommodate to this budget level NOAO was forced to freeze salaries, eliminate all scheduled capital purchases in excess of $20,000, halt all computer acquisition, provide no funding for facilities maintenance, lay off some personnel at CTIO, and slow activity on GONG and FIT. It is obvious that this erosion in all ongoing programs cannot be allowed to continue. Accordingly a review to redefine NOAO’s program is in progress.

The budget for this plan has been prepared prior to completion of that review. For FY 1988 it shows the current plan for expenditures. For FY 1989 it shows the expenditures required to carry out ongoing programs at current levels, with increases only to accelerate GONG to the originally planned level, to provide for unavoidable increases in costs, such as insurance, and to make available approximately $200K each for facilities maintenance and for computer purchases. Since this total substantially exceeds the funding of $24.4M requested in the President’s budget, we show that an unspecified reduction must occur as a consequence of the review that is now in progress. For the remaining years, the budgets from the contract renewal proposal are repeated. These budgets will be revised downward after the review of NOAO is complete.

B. Core Program

The core budget and staffing shown in Table IX includes three components: observatory operations, which includes not only the telescope support but also support for the scientific staff, the instrumentation program, computer services, and the central administration; GONG; and the FTT program. These sections are discussed separately below.

Observatory operations.

We have shown a budget that provides for four percent real growth annually beginning with the first year of the period covered by this plan. Budgetary
increments have been distributed fairly evenly across the four divisions of NOAO in the budget tables, but in practice, and particularly in the early years when budget increases are small, increments would be consolidated and focused to strengthen specific programs or to resolve urgent problems.

Overall, our priorities for incremental funding are: (1) $500K per year for facilities maintenance during the first two years; when the outstanding deficiencies have been corrected, this amount would be reduced to $400K per year; (2) a doubling of the non-payroll support for instrumentation for the four divisions to $1.5M so that we can purchase large format optical and infrared detectors, acquire the powerful new computers necessary for reduction and analysis of the quantities of data produced by these arrays, and subcontract to external groups as appropriate for construction of specific instruments or portions of instruments already developed for other observatories. In terms of scientific staff, the highest priority would be to provide two additional positions at CTIO and NSO. Beyond these initial steps, incremental funding would be used primarily to strengthen the instrumentation program and the development of advanced technology, and to add two scientific staff in Tucson to support these programs, thereby doubling the support for projects during the five years covered by this long range plan. The growth in O&M would provide for operation of two new 4-m telescopes—one at KPNO and one at CTIO, provide observing support for the SYNOP program, and permit purchase of the new Palomar Sky Survey.

GONG.

For the GONG, the budget shows the level of funding that would be required to return to the schedule originally set in the proposal, with only the one year delay imposed by funding levels in FY 1988.

Future Telescope Technology.

For the FTT program, the costs are estimates only, since development of a complete proposal is currently in progress.

C. Initiatives

The budgets (see Table X) for the initiatives are estimates only since design studies are just beginning for the 8-m telescope and the LEST project and are only partially complete for the distributed array.

All budget figures have been inflated by four percent per year relative to FY 1987 dollars. Support directed specifically toward the NNTT will be restricted to design work and site preparation. Support for SYNOP is limited to spectrograph construction and manpower for observing support. It is hoped that capital funding for moderate aperture telescope construction can be obtained from private sources, possibly through partnership with a university.

The total cost of a single 8-m telescope project is estimated at $65M in actual dollars, and it is assumed that the primary mirror and its support system will be provided by funding for the FTT program. The breakdown of costs in FY 1987 dollars for the 8-m telescope is as follows:
The difference between this figure and the total in the budget table is a consequence of inflation. A second 8-m telescope of the same design but on a different site would be approximately two-thirds the cost of the first.

The estimate of $34M for the telescope, building, and site preparation is consistent with the preliminary estimates made by other groups working on 8-m projects. Funding for a new solar facility for high resolution solar observations is estimated on the assumption that NSO will participate in LEST.

D. Management Fee

The management fee charged by AURA covers the cost of the corporate office and staff; the travel and meeting expenses for committees of the Board; required legal, audit, and consulting services; and incidental costs connected with AURA's management of NOAO and ST ScI. These include corporate memberships in the American Astronomical Society and the Astronomical Society of the Pacific, and contributions to meetings of these societies and to educational and training programs in astronomy.

AURA seeks to keep corporate costs low by maintaining a small permanent staff--now only three including the President--and by relying on volunteer service by members of the Board in lieu of corporate staff and in lieu of consultants for expert administrative and other services where possible. As a result, the AURA fee for the operation of NOAO is held to about two percent of the value of the contract with NSF.

The proposed management fee for fiscal years 1990 - 1994 is shown in Table IX.

E. Outlook

With the support and encouragement of the astronomical community and of the NSF, NOAO and AURA can bring about the following vision of the future for ground-based optical and infrared astronomy within the next five years.

- Major capital improvements of aging facilities at national centers can be made, in part, with private funds, including the construction of several 4-m telescopes for Northern and Southern skies, each optimized for its branch of astronomy. Together they will form a carefully planned, coordinated array of research tools. Private contributors and national center users will share in the use of these facilities in rough proportion to funds invested by contributors and the NSF.

- Multiplexed observations of images and spectra, as well as the new telescopes, will have begun to serve the high quality research needs of U.S. astronomy more effectively.
• Mirror technology will have been proven, and several U.S. 8-m telescope projects will be under way in both hemispheres, most of them representing collaborations between several partners—U.S. and foreign. NOAO will be involved with many of these, and will be playing a major role in coordinating the instrumentation and software programs which support them. At least the first of two 8-m telescopes, one in each hemisphere, will be in the advanced phases of construction by NOAO for use by the U.S. astronomical community. Like their 4-m predecessors, the capabilities and objectives of these 8-m telescopes will have been coordinated and become complementary, their costs held down through the use of common technology, and most of them will involve private and national users.

• GONG will have produced exciting data about the solar interior, and NOAO will have defined the limits of angular and polarimetric resolution for ground-based telescopes. An international solar telescope will be under construction with image stabilization technology, with major contributions by NOAO and the Air Force, which will permit it to work at the frontier of solar physics.

• Most uncertainties about the development of nighttime telescopes with apertures beyond 8-m will have been resolved; the community will enthusiastically endorse a major project at NOAO.

Repeated cutbacks in funding have cast doubt on whether this future will be realized, but much of it is still attainable if astronomers cooperate, coordinate their programs and plans, and augment Federal funds by building upon the strong private interest in funding modern research in the discipline. The investment required to bring about this future is modest when compared to the excitement and scientific rewards of modern astronomy. The relationship of astronomy to quantum theory, particle physics and chemistry, and to the understanding of the solar system, the Sun, and the Earth are becoming more apparent as perceived not only by professional astronomers but also by the scientific community at large. The potentially enormous payoffs of a strong U.S. program in astronomy are just beginning to be understood here as they are in Europe and Japan. AURA will continue to work with the NSF and the astronomical community to assure that national ground-based optical and infrared astronomy lives up to its full potential.
# TABLE IX: CORE BUDGET

NATIONAL OPTICAL ASTRONOMY OBSERVATORIES  
FY 1989 - FY 1993 LONG RANGE PLAN  
BUDGET SUMMARY

(Amounts in Thousands)

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<td>Scientific Staff &amp; Support</td>
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<td>Total Observatory Operations</td>
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| Future Telescope Technology:  | $       | $2,023  | $7,727  | $8,498  | $5,006  | $777    |
| Mirror polishing, testing, supports and thermal control (NOAO) | 927     |         |         |         |         |         |
| Mirror Casting Development (U. of Arizona) | 800     |         |         |         |         |         |
| Global Oscillations Network Group | 1,055   | 2,575   | 2,998   | 2,868   | 1,187   | 1,197   |
| Unassigned Budget Reduction |         | <3,110> |         |         |         |         |
| Total Core Budget-NSF Funds | $23,475 | $24,400 | $35,258 | $37,867 | $34,774 | $32,898 |

1 Includes new funds of $22,855K, and $620K carried forward from FY-1987.
2 Observatory Operations budgets for FY 1990 through FY 1993 are from the AURA proposal to the NSF for the operation of the NOAO with minor adjustments to reflect current conditions.
3 FTT budgets for FY 1990 through FY 1993 are from the joint NOAO/Steward Observatory proposal with the schedule slipped by one year. A new plan reflecting the comments of the proposal reviewers is in preparation.
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(Amounts in Thousands)

TABLE III:
NATIONAL OPTICAL ASTRONOMY OBSERVATORIES
FY 1989 - FY 1993 LONG RANGE PLAN
CORE BUDGET SUMMARY BY PROGRAM

76
### Table IXa, continued

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1. Includes new funds of $22,855K, and $620K carried forward from FY-1987.
2. Observatory Operations budgets for FY 1990 through FY 1993 are from the AURA proposal to the NSF for the operation of the NOAO with minor adjustments to reflect current conditions.
3. FTT budgets for FY 1990 through FY 1993 are from the joint NOAO/Steward Observatory proposal with the schedule slipped by one year. A new plan reflecting the comments of the proposal reviewers is in preparation.
4. Includes credit for estimated indirect costs recovered from non-NSF projects ($155K in FY 1988).
5. Includes $35K new funds, and $6K carryover for Research Experiences for Undergraduates (REU) Program.
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**By Function**

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## TABLE I: INITIATIVES

### NATIONAL OPTICAL ASTRONOMY OBSERVATORIES
**FY 1989 - FY 1993 LONG RANGE PLAN**

*(Amounts in Thousands)*

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### Staffing
*(In Full Time Equivalents)*

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