Optical/IR From Ground

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EXECUTIVE SUMMARY

The 1980s witnessed major advances in detector and computer technology, fabrication and polishing of large, lightweight optical elements, and telescope design. In combination, these advances will enable construction during the 1990s of a new generation of large (8-m and 4-m diameter) optical/infrared telescopes. These telescopes will provide an order of magnitude increase in angular resolution, and up to a two order of magnitude gain in sensitivity when compared with current generation telescopes, which are limited by the quality of their optics and by atmospheric turbulence or "seeing". By using actively controlled optical elements to compensate for seeing, and by improving the figure on all mirror surfaces, it will be possible to concentrate the light from unresolved astronomical sources into a diffraction-limited core, and to provide significant gains in image quality for resolved sources. These new generation telescopes must be seen as the harbingers of optical/infrared facilities which by the latter half of the 1990s promise to provide yet another order of magnitude increase in angular resolution.

Thus, for the first time, optical/infrared facilities will have the combination of sensitivity and angular resolution required to observe and analyze

- large samples of galaxies and clusters of galaxies at redshifts $z \geq 1$;
- galaxies at the epoch of their formation;
- protoplanetary disks surrounding young, solar-type stars;

and to provide thereby the observational basis for understanding the *origin* of large-scale structure in the early universe, of galaxies, and of planetary systems similar to our own.

Because these are problems which capture the imagination of both scientists and citizens who share an innate curiosity about our origins and place in the universe, it is hardly surprising that astronomers throughout the world are striving to take advantage of these technological possibilities: our colleagues in Europe and Japan have already been funded to build large O/IR facilities of modern design. For the first time, US leadership in ground-based astronomy–a constant of international science since the beginning of the 20th century–is being challenged. If US astronomy is to maintain its vitality and leadership, it is essential that a new generation of optical/infrared facilities be built during the next decade. We recommend the following program to maintain US competitiveness in O/IR astronomy during the 1990s, and to position the US to establish leadership in high angular resolution O/IR astronomy at the beginning of the next decade.

Large Scale Programs

Priority 1: *A coordinated program to combine federal funds* ($185M) with state and private funds to build and instrument large (8-m class) US ground-based telescopes. The key federal contributions are:

- support for construction of *a pair* of nationally accessible 8-m telescopes, one each in the northern and southern hemisphere. The northern hemisphere telescope will be a *uniquely powerful instrument*, optimized for performance at infrared wavelengths by providing diffraction-limited images (of angular size $\sim 0.05''$ at $\lambda \geq 1.6\mu m$ and minimizing the background thermal emission from the telescope. This unique facility must be built on the best site in the world – Mauna Kea, on the island of Hawaii. Its twin will provide the US astronomical community with the access to the southern celestial hemisphere essential in the era of the NASA Great Observatories, and can be optimized for performance at optical wavelengths.
- support for developing and building the advanced auxiliary instruments required for the new generation of large telescopes – including the recommended pair of national 8-m telescopes, and other US telescopes of comparable aperture which are under construction or in advanced planning stages.
- support to develop and deploy wavefront sensors and adaptive mirrors capable of providing diffraction-limited imaging at near-infrared wavelengths for the new generation of large telescopes.

Medium Scale Programs

Priority 1: *A coordinated program to develop high angular resolution O/IR astronomy which includes federal investment* ($50M) in order to:

- extend the wavelength range (from infrared to optical wavelengths) for full adaptive correction of atmospheric distortion above large telescopes;
- support engineering efforts to design an ultra-large (D $\geq$ 30-m), adaptively-corrected single-aperture telescope;
- support university-based efforts to build and operate pilot interferometers;
- support a university-based effort to develop a sensitive O/IR interferometer array by mid-decade;
- support engineering studies leading to the design of a large, national O/IR array capable of imaging celestial objects with at least ten times the angular resolution of 8-m class telescopes and at comparable or greater sensitivity.

Priority 2: *A program to construct at least four, new-generation 4-m class telescopes.*

These telescopes will provide the basic tools necessary to carry out a wide variety of large-scale surveys, innovative observational programs, and basic research aimed at deeper understanding of known astrophysical phenomena. It is highly desirable that these telescopes be constructed by individual universities and university consortia. The most immediate community need is for two new generation 4-m class telescopes (one in each hemisphere) to support and complement the Great Observatories. Construction of four new-generation telescopes will require a combination of federal ($30M), state and private funds.

Small Scale Programs

Priority 1: *A program to carry out near-infrared and optical all-sky surveys with digital arrays* ($11M)

These surveys will produce complete, unbiased infrared and optical maps of both celestial hemispheres, and will thus provide an essential database for planning space-based missions and major observing programs on large, ground-based telescopes.

Priority 2: *A program to develop a National Astrometric Facility* ($5M)

The NAF will provide the ability to obtain ultra-precise (better than $0.001''$) positions of celestial objects both within and outside the solar system.

Infrastructure Support

Priority 1: *A program to fund the development, purchase and distribution of large format optical and infrared detectors* ($40M)

The ready availability of advanced panoramic detectors is absolutely essential to the development of sensitive instruments for the new generation of large telescopes, and thus to achieving the full power and potential of these major facilities.

Priority 2: *A program to fund the fabrication and polishing of large mirrors, specialized optics, and the development of mirror coating techniques (*\$25M).

The availability of large ($\geq$ 4 m diameter) accurately polished lightweight mirrors, correcting optics, and mirror coatings underlies our ability to build new generation telescopes, and the auxiliary instruments required to enable their most efficient use.

OPTICAL/INFRARED ASTRONOMY IN THE 1990S

Research Environment

The advances in detector and computer technology of the 1970s and 1980s, combined with our ability to observe the universe throughout the electromagnetic spectrum by using powerful space- and ground-based telescopes, have revealed new phenomena (e.g. evidence of gravitational lenses; x-ray emission from clusters of galaxies and globular clusters; gamma-ray bursters; infrared luminous starburst galaxies; energetic winds emanating from obscured protostars), and heretofore unknown structures (e.g. the tapestry-like structure of the universe as revealed by 3-dimensional maps of galaxies; concentrations of unseen matter which locally alter the expansion of the universe; collimated jets of plasma driven by young stars; infrared luminous protoplanetary and perhaps post-planet building disks) and have forced astronomers to view the cosmos from new perspectives. The drive to understand these phenomena, and to place them in the context of current paradigms if possible (or to create new ones if necessary), motivates the development of ever more powerful experimental techniques.

The 1990s promise to be one of the most exciting decades in the history of astronomy. During the next ten years, NASA will launch the Gamma-Ray Observatory (GRO), the Advanced X-Ray Astrophysics Facility (AXAF), and the Space Infrared Telescope Facility (SIRTF). Together with the Hubble Space Telescope (HST) launched in April, 1990 these "Great Observatories" will provide revolutionary tools for exploring the universe at wavelengths throughout the electromagnetic spectrum.

As astronomy enters this new era, *ground-based optical/infrared facilities will play a central role.* Large ground-based telescopes are required to provide the sensitivity needed for spectroscopic analysis of phenomena discovered with the Great Observatories. Extensive observations with moderate-size and smaller survey telescopes are essential to (1) selecting targets for the Great Observatories; and (2) providing the context for understanding objects and phenomena discovered at other wavelengths (identification of gamma- and x-ray sources, for example).

Ground-based optical/infrared telescopes also promise to be powerful engines of discovery in their own right. Dramatic advances in detector technology, telescope design, and computer controlled optical elements during the 1980s, provide the technical basis (see below) for constructing a *new generation* of large ground-based optical/infrared telescopes and auxiliary instruments capable of providing 10 times the angular resolution and up to 100 times the sensitivity of currently available ground-based telescopes.

These same technological advances, combined with the results of innovative experiments carried out in the US and in Europe, promise that by the beginning of the next century, it will be possible to build interferometric arrays – the optical/infrared analogs to the cm-wavelength Very Large Array (VLA) and the proposed millimeter array (MMA). Such optical/infrared arrays will provide images with an angular resolution 500 times better than the finest images taken on the ground in 1980 and 10 times the quality of the images expected from HST.

Science Opportunities

The anticipated gains in angular resolution and sensitivity from new generation large telescopes and interferometers provide immense opportunities for new scientific discoveries and for achieving deep understanding of phenomena which lack ready explanation within current paradigms. Outlining the "science opportunities" provided by devices which will provide order of magnitude improvements in *two* parameters of "discovery space" –angular resolution and sensitivity– is a challenging exercise, depending as it must on extrapolating from the frontiers of knowledge reached only a few years ago. We have chosen to meet that challenge by *illustrating* the potential of these new tools for enabling major advances in understanding three areas – the origin of structure in the universe, the origin and evolution of galaxies, and the origin of stars and planetary systems.

The Origin of Structure in the Universe

Prior to 1980, observational cosmology could be defined as the search for two numbers: H_o and q_o, the expansion rate of the universe and its rate of change. Even though exact values for these two numbers have remained elusive, cosmology in the 1980s came to include the formation and evolution of large scale structures in the universe, and the origin and distribution of massive aggregates of galaxies and matter which (locally) distort the uniform expansion of the universe (the Hubble flow).

Advanced detectors enabled the determination of redshifts (recession velocities expressed in units of the speed of light) for large samples of relatively nearby galaxies and, in combination with extant imaging surveys provided the first *three-dimensional* (distance from earth, in addition to the projected location on the celestial sphere) maps of the distribution of galaxies in local universe. The result was both startling and unexpected: galaxies are not distributed randomly in space, but appear to lie along thin, web-like structures separated by great voids. Over what scales do these web-like structures persist? At present we don't know – because despite ten years of concerted effort we have been able to provide a 3-dimensional map covering only 0.01 percent of the potentially observable universe.

The 1980s also witnessed the development of new techniques to measure the relative distances to galaxies – for example the relations between velocity dispersion or rotation velocity and a galaxy's integrated luminosity or size. Plots of galaxy recession velocity (obtained from spectroscopic measurement of doppler velocity) against the distances derived from the these new indicators, revealed local changes in the expansion rate of nearby galaxies which astronomers attribute to a massive aggregate known as the "Great Attractor." Whether the "Great Attractor" is unique, or representative of a large number of such aggregates is unknown, because at present we have accurate relative distances to fewer than 1000 galaxies. Accurate measurements of distortions in the Hubble expansion rate are needed to determine the gravity field and match it to the galaxy distribution – to test for the existence of "dark" (unseen) matter in the universe, and if found, to measure its quantity and location.

During the 1990s, the construction of new generation 4-m and 8-m class telescopes will enable great strides in understanding the structure and distribution of matter within the universe. Three fundamental goals for observational cosmology in the 1990s are:

- to map the 3-dimensional distribution of "nearby" galaxies to redshifts $z \sim 0.1$. This program will require measurements of redshifts for 1 million galaxies selected from deep, uniform, all sky surveys. Because these systems will be 5 to 10 times fainter than those surveyed to date, it will be necessary to carry out the redshift measurements with new generation 4-m class telescopes equipped with multi-object spectrographs capable of simultaneous observations of hundreds of galaxies over a 2° field. Even with such powerful facilities, it will require ~6 years per celestial hemisphere to observe the ~ 1 million galaxies necessary to complete this redshift survey.
- to map the gravity field – deduced from distortions in the uniform Hubble expansion – out to a redshift $z \sim 0.03$. To carry out this program requires accurate relative distances to approximately 10,000 galaxies. Distances can be obtained with accurate photometry, made available from deep all-sky surveys, and measurements of galaxy velocity dispersions or rotational velocities. To make these latter measurements requires approximately 1 hour per galaxy on a new generation 4-m class telescope. Because these nearby galaxies are relatively isolated, simultaneous measurements with multi-object spectrographs cannot provide major increases in observing efficiency. The basic program will thus require more than 5 years to complete.
- to study the evolution of large-scale structure in the universe by mapping the distribution of galaxies and clusters of galaxies at $z \geq 1$, and comparing structures in the young, distant universe with "old", nearby structures. This requires that we complement our map of the nearby ($z \leq 0.1$) galaxy distribution, with redshift determinations for galaxies at redshifts near and beyond unity. Appropriate samples of distant galaxies must be assembled from small area, deep imaging surveys with 4-meter class telescopes, and x-ray (ROSAT and AXAF) surveys for galaxy *clusters*. To sample a region comparable to the 1 million

galaxy "local" survey will require redshifts for $\sim$100,000 distant ($z \geq 1$) galaxies to a magnitude limit of B=24 in a 100 square degree area. Obtaining redshifts of this large a sample of faint galaxies will be *enabled* by new generation 8-m class telescopes. Even so, this project will require approximately *5 years* on an 8-m class telescope equipped with a multi-object spectrograph capable of observing 100 galaxies simultaneously. Such a survey would, however, be of profound importance: it would allow detailed comparison of the topology of structures in the universe now, and at an epoch when the universe was less than 30 percent of its current age.

The Origin and Evolution of Galaxies

During the 1980s, astronomers carried out challenging spectroscopic observations which led to the discovery of the most distant systems known in the universe: quasars with redshifts $z \geq 4$, and radio galaxies with $z \geq 3$. These observations provide evidence that some, perhaps the majority of galaxies must be assembled and must begin forming stars at $z \geq 5$, and thus provide strong motivation to extend current searches to higher redshifts (earlier epochs in the life of the universe) in order to locate galaxies just taking form from protogalactic clouds. Identifying the epoch of galaxy formation, defining the structure of young galaxies, and characterizing star formation and chemical element production early in the lifetime of these systems, represent fundamental steps toward understanding the origin and evolution of galaxies.

At $z \geq 5$, galaxies will be faint ($K \geq 22$ mag), their angular size will be small ($3''$ to $10''$), and light from the visible region of the spectrum will be shifted to the 2 μm window. Comparison of the structure and chemical composition of these distant young systems with that of more evolved systems at lower redshift – and thus charting their early evolution – will require sensitive, high angular resolution imaging and spectroscopy in the infrared. It is the infrared which carries fundamental information regarding the underlying structure of the galaxy through its sensitivity to light emanating from intermediate and low mass stars–the likely dominant constituents of these systems, optical measurements will likely be overwhelmed by (restframe) ultraviolet light emerging from complexes of newly-born massive stars. Infrared spectroscopy of red-shifted emission features such as [O III] and Hβ will provide the basis for determining chemical composition and estimating the vigor of star-forming events.

New generation 8-m telescopes will *enable* the study of forming galaxies:

- by locating candidate forming galaxies by means of deep optical and infrared images which measure galaxy color, emission line strength, and morphology (based on high angular resolution images). With current generation 4-m class telescopes, deep imaging of galaxies with $K \sim 21$ mag requires 12 hours of integration. Surveys to the even fainter limiting fluxes required to locate galaxies at $z \geq 5$ must be carried out with 8-m telescopes. Because these faint galaxies must be viewed against the background emission from the telescope, it is also essential that one or more of these telescopes be designed for low emissivity operation in the infrared. Furthermore, the likelihood that forming galaxies will exhibit small-scale structure (nuclear starburst regions; giant H II complexes) places great premium on high angular resolution in order to achieve maximum sensitivity in imaging forming galaxies at high redshifts, and in characterizing their morphology.
- through their ability to measure redshifts for these extraordinarily faint systems. Redshift determinations for systems at $z \geq 3$ at optical wavelengths require hours of time on current generation 4-m class telescopes, and are not yet possible in the near infrared even on the largest available telescopes. The new generation of 8-m telescopes will provide the increase in sensitivity necessary to *enable* redshift measurements and spectroscopic analyses of systems beyond $z = 3$, and the power necessary to observe the large samples of forming galaxies over the redshift range $z \geq 5$ to $z \sim 2$ required to understand the galaxy birth process and the early evolution of these systems.

The Origin of Stars and Planetary Systems

Before 1980, it was known that stars form in cold, dark aggregates of matter known as "molecular clouds." Studies of the stellar populations of young stars just emerging from stellar wombs had provided astronomers with a rudimentary picture of how these objects evolve prior to igniting hydrogen in their cores and becoming stable, main sequence stars. During the 1980s, sensitive mm-wave, optical and infrared measurements from the ground, and the launching of the IRAS satellite provided a number of profound surprises and revolutionized our understanding of the star formation process:

- mm-line observations of molecular clouds revealed that stellar birth is a violent process, accompanied by energetic outflows, sometimes mapped by highly collimated jets of hot plasma;

- IRAS observations at infrared wavelengths revealed emission from extraordinarily young stars, still being assembled from material contained within dense, opaque protostellar cores which obscure the birth process at optical wavelengths;
- IRAS and ground-based infrared images of molecular clouds revealed that some clouds seem to produce new stars quickly and with high efficiency, while others form stars more slowly and convert only a small fraction of their store of molecular material into stars;
- Ground-based, IRAS, and mm-continuum photometric measurements, along with high resolution spectroscopic observations made it plain that a large fraction of solar-type stars are surrounded by disks of solar-system dimension and of mass comparable to or greater than the mass of material out of which our solar system is thought to have formed;

During the 1990s, a variety of new and powerful instruments – HST, ISO, SIRTF, SOFIA , single dish mm- and sub-mm wave telescopes, and mm interferometers – will enable qualitatively new kinds of measurements which should effect even more dramatic transformations in our understanding of star and planet formation.

Ground-based O/IR telescopes of diameter ~8-m will play a central role in our quest to understand stellar and planetary birth by virtue of their potential to provide both diffraction-limited images from 1.6 μm to 20 μm , and light gathering power sufficient to permit ultra-high resolution spectroscopy of young stars and their circumstellar environs.

The new generation 8-m class telescopes will permit us for the first time:

- to obtain infrared images and spectra of extraordinarily young stars, associations, and clusters deeply embedded within their natal cores, and to understand the relationship between star formation efficiency, the stellar initial mass function and the physical properties of parent cores and molecular clouds. Equipped with adaptive optics, such telescopes will be sufficiently powerful to allow us to image forming stars and clusters even in cores obscured by up to 50 magnitudes of visual extinction and to separate young stars in newly-formed stellar clusters with densities exceeding 2 x10^4 stars pc^{-3}, and to obtain the photometric and spectroscopic measurements necessary to place these objects in the HR diagram – not only in relatively nearby regions of low mass star formation, but also in more distant molecular clouds where much rarer high mass PMS and young MS stars must be studied. What kinds of clouds/cores give rise to high mass stars and how do they differ from regions where low mass star formation is the rule? Is star formation in the Milky Way and other galaxies bimodal? Under what conditions do bound clusters, multiple and binary stars form? How does the early evolution of high mass stars differ from their low mass counterparts?
- to obtain images of solar system-size circumstellar disks surrounding nearby solar-type PMS stars with unprecedented clarity, and to study the kinematic properties of such disks. By use of adaptive optics, we can trace the distribution of solid material within the disk at effective spatial resolutions of ~ 5 to 10 AU, by observing light scattered by circumstellar dust. By virtue of their large collecting area, 8-m class telescopes will allow us to obtain disk rotation curves from analysis of R ~100,000 infrared spectra of photospheric light scattered by circumstellar dust, or of resonantly-scattered molecular line radiation.
- to study the gas content and gas/dust ratio for circumstellar disks throughout the disk, and as a function of time. The photon gathering power and high spatial resolution of 8-m class telescopes will allow us to trace emission from CO, NH_3, SiO, and from small (50 atom) grains as a function of position within disks surrounding stars of differing age, and to compare the observed distribution of gas with that of the dust as inferred from infrared imaging and photometric measurements. Can we observe gas rich disks – the structures expected following the assembly of distributed disk dust into planetesimals? Over what range of ages can we detect disk gas and how severe a constraint does the gas survival time place on the timescale for assembling giant, gas-rich planets similar to Jupiter? What role do T-Tauri winds play in dispersing the disk gas?
- to obtain multiple high spatial resolution images of collimated stellar outflows ("jets") emanating from embedded young stars, in order to learn how these structures become collimated, and how they evolve. With adaptive optics, 8-m class telescopes will provide a spatial resolution of ~ 0.05″ at 1.6 μm, which will allow us to obtain images and spectra of jets to within 5 to 10 AU of the stellar surface, and to define their relation to disk and protostellar core structures. By observing embedded and emerging

PMS stars of differing ages, we can learn whether outflows remain highly collimated throughout the phases of PMS star evolution when disks are present. If they do, how are gas and dust cleared from post-planet building disks?

- to obtain images and spectra of substellar mass, close companions of PMS stars. 8-m class telescopes will provide the photon-collecting power to derive accurate effective temperatures from moderate resolution spectra, and luminosities from broad-band photometry, for sub-stellar objects of luminosities as small as 10^{-5} $L_{\odot}$. With adaptive optics providing diffraction-limited images at 1.6 μm, such objects can be imaged at separations as small as 10 AU from a companion PMS star in the nearest star-forming complexes. By locating substellar mass objects associated with PMS stars, we will 1) be observing them at their earliest evolutionary stages when they are expected to be most luminous, 2) be able to determine their approximate ages (from the ages of their PMS companions), and thereby to confront theories describing the evolution of such objects, and 3) to determine whether low mass companions are likely formed within the circumstellar disk of a parent PMS star, or via a separate fragmentation and collapse process within a common molecular core. Do large planets and ultra low mass stars have a common origin or is one class of objects assembled within disks and the other form via fragmentation?

To observe the terrestrial planet-forming regions of pre-planetary disks will require an order of magnitude gain in angular resolution, and thus the development of ground-based optical/infrared interferometers. Such interferometers can provide the angular resolution and sensitivity necessary to probe the structure of planet-forming disks around several hundred nearby ($100 \leq d \leq 200$ pc) young solar-type of ages ranging from 1 Myr to 20 Myr, and will for the first time *enable* astronomers to image planetary systems in differing stages of development.

Technical Developments of the 1980s and Opportunities for the 1990s

Our ability to design the facilities and instruments which enable these fundamental investigations results from advances in telescope and detector technology during the 1980s.

Advances in Telescope Technology

In its review of astronomy at the beginning of the 1980s, the Field Committee strongly recommended investments aimed at developing the technology to enable the construction of a new generation of large optical telescopes. Vigorous efforts involving a combination of private, state and federal resources have led to a veritable revolution in our thinking about large telescopes: as we enter the 1990s, almost every aspect of telescope design is viewed from a dramatically different perspective:

- Two approaches for constructing large primaries were developed:
    - (1) active primary mirror surfaces comprised of multiple glass mirror segments
    - (2) monoliths of ultra-lightweight honeycomb borosilicate glass
- New polishing techniques were developed which enable reduction of telescope focal ratios, from f/3 to ~f/1, with a corresponding ~threefold decrease in overall telescope size relative to mirror diameter;
- Finite element analysis enables thorough and accurate analysis and optimization of mechanical and optical support structures;
- Advances in control systems (computers and electronics) enable the design of active control systems for monitoring and correcting mirror figures and maintaining the performance of the entire optical system;
- Advances in understanding the influence of wavefront distortion introduced by the local telescope environment provide the potential for dramatic improvements in image quality through reduction of "dome seeing";

These advances have enabled the planning of a new generation of large (8-m and 4-m diameter) optical/infrared telescopes which will provide higher image quality and superior overall performance than any telescopes built to date, and can be built at far lower cost per square meter of collecting area.

In order to remain at the forefront of astronomical research worldwide, it is necessary to take advantage of these technological developments to construct a new generation of optical/infrared telescopes in the United States.

Advances in Detector Technology

While no major ground-based optical/infrared telescopes were constructed in the United States during the 1980s, ground-based O/IR astronomy nevertheless witnessed a revolution in observing power, driven in large measure by the introduction of sensitive, large format optical (charge-coupled devices, or CCDs) and infrared arrays. US astronomers have incorporated these array detectors in a variety of instruments which have multiplied the sensitivity of extant telescopes by factors of tens to hundreds. These advances are a direct result of United States leadership in the development of sensor technology.

- *At optical wavelengths* CCDs (now of dimension 2048x2048 pixels) provide an order of magnitude improvement in sensitivity over previous detectors, and offer major improvements in geometric and photometric stability. Introduction of large format CCD detectors has enabled high precision photometric studies of stars and galaxies, monochromatic imaging, sensitive multi-object spectroscopy of stars and galaxies, and high (S/N $\gg$ 100) signal/noise echelle spectroscopy.
- *At infrared wavelengths,* array technology has progressed dramatically during the past 5 years. In the wavelength regime $\lambda \leq 5\mu$m, devices as large as 256x256 pixels have rapidly replaced the single detector systems which, until the mid-1980s, were the standard. It is now possible *for the first time* to image astronomical objects at infrared wavelengths, to obtain spatially resolved spectra of extended sources, and to build high spectral resolution cryogenic echelle spectrographs.

During the next decade, it will be necessary to build larger format optical and infrared detectors characterized by lower read noise, faster read times, and broader wavelength response. It is imperative that astronomy take full advantage of US strengths in advanced optical and infrared sensor technology to develop array detectors matched to the new generation of O/IR telescopes. Detector performance *and availability* are *sine qua non* for competitive instrument performance on all telescopes.

It will thus be necessary to make a strong commitment to continued development of advanced sensors, and to evolve strategies for bulk purchases and distribution of detectors for use by the US astronomical community.

Auxiliary Instruments

The availability of sensitive array detectors and the rapid evolution of sophisticated image analysis techniques enabled by advanced computer technology, has led to development of instruments far more complex and powerful than the photometers and spectrographs built prior to 1980. Among the most dramatic advances have been:

- the introduction of spectrographs capable of obtaining spectra of large numbers of stars or galaxies simultaneously. Multi-object spectrographs can reduce observing time for many survey programs by ~100-fold.
- the development of cryogenically-cooled infrared spectrometers which enable two-dimensional spectroscopy of infrared sources at moderate spectral resolution, and promise within the next year ~1000-fold gains in sensitivity for carrying out high spectral resolution studies.

The availability of more advanced array detectors will enable more powerful versions of these and other instruments to be constructed during the 1990s, and will extend their capabilities to broader wavelength ranges. In order to take full advantage of the potential gains offered by telescopes of advanced design, it will be necessary to develop instruments matched specifically to these telescopes.

The new generation of large telescopes will require a major investment in instrumentation which will differ in scale and design from the instruments of the 1980s.

Pioneering a New Frontier: High Angular Resolution O/IR Astronomy

The advances of the past decade enable the design and construction of a new generation of ground-based optical/infrared facilities which can provide order of magnitude gains in angular resolution and sensitivity Indeed, the 1990s promise to be the decade in which astronomers throughout the world exploit these advances to pioneer a new frontier: high angular resolution infrared and optical astronomy.

A deep, long exposure of an astronomical object, even one taken with a large optical/infrared telescope located at the best site in the world, at present produces images of point sources which are blurred to a diameter of $\geq 0.5''$, and will thus not reveal details on resolved sources on angular scales smaller than $\sim 0.5''$. This image blurring, or "seeing" results from distortions in the incoming wavefront produced by the combined effects of multiple, rapidly moving turbulent elements at all levels in the earth's atmosphere above the telescope. If the atmosphere were removed, that same telescope would *concentrate* the light from a star into a diffraction-limited core (of dimension $0.02''$ at 0.55 μm, and $0.05''$ at 1.6 μm for an 8-m telescope), and would *resolve* features comparable in size to the diffraction limit in extended sources.

The strong desire to overcome the limitations imposed by the atmosphere in order (1) to improve our ability to detect faint point sources; (2) to improve the image clarity for resolved, often distant sources and (3) to *enable* for the first time the resolution of structures hidden from view by the "blur" introduced by the atmosphere, were among the primary factors motivating the development of the Hubble Space Telescope. Even though the HST mirror is of only modest (2.3 m) size by current ground-based standards, its location above the earth's atmosphere can potentially provide a *diffraction-limited* image which results in a $\sim$ 100-fold increase in sensitivity for point sources and a 10 times increase in angular resolution at ultraviolet and optical wavelengths.

Even the resolving power of HST will be unable to probe the centers of active galaxies, to image forming galaxies, or to resolve the terrestrial planet-forming regions around solar-type stars. These and other exciting problems have motivated astronomers worldwide to design and build telescopes and instruments capable of providing even greater sensitivity and image clarity. During the 1980s, instrumentalists have developed a variety of novel techniques for improving the image quality achieved with ground-based O/IR telescopes. The results of their efforts have borne fruit, and during the 1990s will enable:

- sensitive imaging with diffraction-limited resolution (0.05″ at 1.6 μm and 0.02″ at 0.55 μm) using the full aperture of 8-m class telescopes by means of a technique known as *adaptive optics* ; by comparison, HST will provide images of size $\sim$ 0.07″ at 0.55 μm. At this angular resolution, it will be possible to study stellar populations in the nuclear bulges and disks of nearby galaxies, probe the planet-forming regions of primordial solar nebulae, and image solar system bodies to resolutions of $\sim$75 km at the distance of Jupiter.
- imaging with potential angular resolutions of $\sim$0.002″ at 1.6 μm and $\sim$0.0005″ at 0.55 μm with *interferometric arrays* of moderate-size telescopes separated by $\sim$200 meters. At this angular resolution it will be possible to image the narrow emission line regions of active galactic nuclei, accretion disks in close binaries, and expanding envelopes surrounding late-type stars.

Adaptive Optics

Adaptive optics is a technique which makes use of sensitive array detectors and high performance computers (1) to detect and model the amount by which an incoming plane wavefront from a celestial source is altered by the atmosphere (using a a device known as a "wavefront sensor"); and (2) to use that information to command a fast servo system to alter the figure of a flexible optical element (an "adaptive mirror") by an amount necessary to compensate for constantly varying atmospheric distortions.

There are *three* parameters that are basic to understanding the vocabulary of and concepts underlying adaptive optics. The *first* is r_0, the *atmospheric correlation length.* An incoming plane wavefront from a celestial source is distorted randomly by moving turbulent elements in the atmosphere above the telescope. One can think of the primary mirror as comprised of a large number of patches, each of dimension r_0, over each of which the wavefront is approximately (and instantaneously) flat, *but tilted* relative to its neighboring r_0 patch; the patch-to-patch *tilt* differences correspond to *phase differences in the incoming wavefront. The parameter* r_0 is the characteristic spatial scale over which the rms phase differences (or wavefront tilts) are less than one radian. At 0.55 μm, $r_0 \sim$ 20 cm under conditions of of excellent (0.5″) seeing. The "wavefront sensor" uses a bright reference object (either the star itself, a nearby star or an artificial star) to model the distortions in the incoming wavefront wrought by the earth's atmosphere in terms of an ensemble of wavefront tilts over the $(D/r_0)^2$ patches covering the primary mirror (of diameter D).

The *second* parameter is τ_0, the *atmospheric correlation time.* If one imagines the turbulent elements responsible for atmospherically-induced wavefront disturbances as being swept rapidly past the telescope by the wind at some speed, v, then the characteristic time over which the wavefront tilt over a given r_0 patch changes by one radian is $\tau_0 \equiv r_0/V$. For a typical windspeed of 10m/s, τ_0 is typically 20 msec at 0.55 μm.

The *third* parameter is i, the *isoplanatic patch angle.* If one imagines a pair of stars, A and B, separated by an angle i, then i is the separation within which the *relative* tilts of the wavefronts emanating from A and B do not exceed one radian; i is thus the angle subtended by a patch of dimension r_0 viewed from the height of the atmospheric layer where the wavefront tilts originate. The characteristic height of this layer above the telescope is or order 10 km, so that at 0.55 μm, $i \sim 4''$.

The challenge of adaptive optics is to sense *wavefront tilts* in a time short compared with the *atmospheric correlation time* by using the imaged celestial source itself or an adjacent source which lies within the *isoplanatic angle,* and to signal corrections to a flexible adaptive mirror equipped with $(D/r_0)^2$ actuators. In Table 1, we summarize characteristic values for r_0, τ_0, and i, assuming 0.5″ seeing, an 8-m telescope and

Table 1. Characteristic Parameter Values for 0.5″ seeing, 8-m telescope 10 m/sec windspeed

λ (μm)	r_0 (cm)	$(D/r_0)^2$	τ_0 (msec)	(λ/D) (arcsec)	iso-angle (arcsec)
0.5	20	1600	20	0.013	4
0.9	40	400	40	0.026	8
1.6	84	90	84	0.042	17
2.2	118	46	118	0.057	24
4.8	300	7	300	0.124	62
11.0	816	1	816	0.284	142

a (typical) wind speed of 10m/s. This table illustrates the *dramatic differences* in the complexity of adaptive correction systems as a function of wavelength: it is *far easier* to effect adaptive corrections in the *infrared* because (1) fewer actuators are required; (2) the wavefront tilts can be measured more easily using fainter reference stars because the correlation time is longer and the effective "collecting area" that can be used is proportional to r_0^2; and (3) more reference stars are available for effecting adaptive corrections for faint sources because $r_0, \tau_0,$ and i are larger.

Early applications of adaptive optics by European astronomers working with the 3.5m NTT in Chile have already produced images at 2.2 μm in which a large fraction of the power is contained *within a core whose size is that of the diffraction limit of the telescope.* Experiments underway at the University of Hawaii suggest that dramatic gains in image quality at near-infrared wavelengths may be achieved with very simple adaptive mirrors having relatively few actuators, $N \ll (D/r_0)^2$. These results make us confident that *full adaptive corrections will be possible at $\lambda \geq 1.6\mu m$ within a few years.*

In contrast to the infrared, adaptive corrections at optical wavelengths require thousands of actuators to deform the adaptive mirror. Moreover, the paucity of bright reference sources expected within the smaller isoplanatic angle make it necessary to consider developing an artificial reference star for use at optical wavelengths. In this scheme, a bright laser beam is used either to excite sodium atoms in a layer at the top of the atmosphere, or to backscatter off air molecules. By suitably focusing the beam of the pulsed "laser star" onto the relevant disturbing layer in the atmosphere and timing the return laser pulses, one can sense and correct the wavefront tilts once every τ_0. Clearly, investment in a major technology development program will required in order to provide full adaptive corrections at optical wavelengths.

Ground-Based Optical/Infrared Interferometry

During the 1980s, astronomers made great strides in another very promising direction for achieving ultra-high angular resolution: *optical/infrared interferometry.* The technique of combining and interfering beams from widely separated telescopes has been used for more than four decades by radio astronomers to provide high angular resolution imaging at cm- and more recently at mm- wavelengths. The challenge of constructing an interferometric array is far more daunting at O/IR wavelengths primarily because the earth's atmosphere is far less benign at these wavelengths. Atmospheric distortion of incoming wavefronts from celestial sources vastly complicates efforts to track interference fringes, and to make use of the full aperture of each component of the array.

Despite these problems, great progress has been enabled by advances in both computer and detector technology, and by the ingenuity of pioneering experimentalists:

- fringe tracking for significant time periods was first achieved in the mid-1980s by a team of French astronomers operating a two-element optical interferometer at baselines ~100 meters. US groups have recently enjoyed major successes as well, and appear on the verge of developing imaging interferometers capable of observing bright optical and infrared sources.
- astronomers in the US made use of the separate 1.8m mirrors comprising the Multiple Mirror Telescope to establish the feasibility of interferometric imaging over fixed baselines of ~10m; This success with

the MMT led European and US astronomers to design the Very Large Telescope, the Keck telescope, and the Columbus Project to provide interferometric capability with fixed baselines.

- a number of pioneering groups in Europe and the US have begun to build interferometric arrays of small telescopes operating both at infrared and optical wavelengths, and over variable baselines ranging up to several hundred meters.
- parallel advances in adaptive optics technology offer the promise of making use of the *full area* of large array elements, and thus of building imaging systems capable of *high sensitivity* observations at infrared, and later, optical wavelengths.

Interferometry, first with fixed baseline arrays of ~20-50m, and later with variable baselines extending to several hundred meters or longer, promises to provide infrared and optical images with angular resolutions exceeding 0.002″.

The ability to study the optical/infrared sky at high sensitivity and at angular resolutions 10 times and later 100 times current capabilities will enable new of classes of astronomical research. Interferometers will allow us for the first time to *image* the surfaces of stars, to observe planets outside the solar system, and to image the regions surrounding the engines which power active galactic nuclei.

It is imperative to invest in a major effort aimed at developing high angular resolution astronomy at optical/infrared wavelengths (1) by developing and applying adaptive optics technology to enable sensitive diffraction-limited imaging by large ground-based telescopes, and (2) by combining adaptive optics and interferometry to produce sensitive imaging at resolutions 0.001″ and greater. Support of this pioneering effort will be essential to maintaining US leadership at the frontiers of astronomy at the beginning of the next century. Such investments would represent a continuation of a strong US commitment to developing technically advanced radio interferometers which provide the highest feasible angular resolution– beginning with the Very Large Array (operating at cm wavelengths) in the 1970s, continuing with the Very Long Baseline Array (cm wavelengths) in the 1980s and culminating with construction of the Millimeter Array in the mid- to late- 1990s. The technology base developed in the 1980s combined with a vigorous development program in the 1990s, will provide the basis for designing an optical/infrared analog of the VLA during the the 1990s, and building the array during first decade of the next century.

Ground-Based Optical/Infrared Astronomy Outside the US

Our colleagues in Europe and Japan have recognized that leadership in astronomical research requires investment in a new generation of optical/infrared facilities. The Japanese government is committed to building an advanced technology 8-m class telescope on Mauna Kea in Hawaii. The European Southern Observatory (operated by a consortium of European countries) has just completed a 3.5-meter diameter New Technology Telescope. Equipped with an active system to control the mirror figure, and with adaptive optics to compensate for the blurring effects of the earth's atmosphere, the NTT has recorded the sharpest images ever made from the ground. ESO has also committed more than $200M toward the construction of a powerful, technically advanced optical telescope – the Very Large Telescope. The VLT, with an equivalent collecting area of 16-m, provides more than twice the light gathering power of the largest planned US facility. The VLT promises gains not only in light gathering power, but in angular resolution as well. When fully operational, the VLT can be operated as an interferometric array, capable of providing optical images with angular size 0.005″. These facilities will provide astronomers in Europe and Japan with the tools needed to carry out frontier research in the era of the Great Observatories.

As scientists, we rejoice in the success of our colleagues in other countries and look forward to the discoveries which will inevitably ensue as the power of these new facilities is unleashed. As citizens, we are concerned that US leadership in astronomy (as in other sciences) is presently based largely on returns from investments and plans made in the 1960s and 1970s. *Without a strong commitment in the 1990s to join the competition for astronomical leadership worldwide, the relative quality of US astronomy will inevitably decline.*

Central to US competitiveness in astronomy is the development of world class ground-based optical/infrared facilities. In the following sections, we recommend an investment strategy – based on the technical and scientific opportunities we perceive for the next decade – aimed at preserving US competitiveness in ground-based O/IR astronomy during the 1990s and positioning the US to establish leadership in high angular resolution O/IR astronomy at the beginning of the next century.

RECOMMENDATIONS OF THE PANEL: LARGE SCALE PROGRAMS

Priority 1: A Coordinated Program For Large O/IR Telescopes

Background

Ground-based optical and infrared observations of faint celestial sources are currently limited in sensitivity by the amount of light telescopes can collect and measure, by the brightness of atmospheric and telescope emission, and by the blurring of images introduced by the earth's atmosphere. In the past, improvements in detector efficiency and instrument design could provide large increases in sensitivity at relatively modest cost. However, detector performance is now pressed close to theoretical limits, owing in great measure to US leadership in developing advanced optical and infrared array sensors with quantum efficiencies approaching unity. Hence, major improvements in *telescope* performance are necessary in order to provide the sensitivity to address frontier problems in astronomy.

Following a decade of successful technology development, optical and infrared astronomers are poised to build a new generation of powerful ground-based telescopes. Major advances in telescope collecting area, the optical quality of large mirrors and overall telescope systems, and in the image quality produced by earth-bound telescopes through the use of adaptive optics, promise a 10 fold increase in angular resolution and up to 100 fold the sensitivity of the largest extant facilities. These advances will *enable* qualitatively new astronomical observations. *We therefore recommend a vigorous program for the development of 8-m class telescopes in the United States. This program includes as an integral component, development of the adaptive optics systems and the auxiliary instrumentation required to realize the full potential of these frontier research tools.*

New Science Enabled by Greater Collecting Area

The first gains to be realized by large telescopes are in sensitivity–achieved simply as a result of their larger collecting area. We list below *examples* of key programs which would require years or decades of observing time on existing 4-m telescopes. Further progress on these programs thus awaits the increase in collecting area provided by 8-m diameter telescopes:

- determining the large-scale structure of the universe at early epochs through measurement of redshifts for large ($\sim$100,000) samples of galaxies at high redshift ($z \geq 1$);
- determining the distribution of quasars in space and time, especially at early epochs ($z \geq 3$) where quasars illuminated the universe for the first time;
- probing the chemical evolution of galaxies as a function of lookback time from high resolution spectroscopic observations of metal lines produced in multiple intervening galactic halos and seen against the background light of distant quasars;
- comparing the age of the Universe as derived from the Hubble expansion parameter with accurate age determinations for the oldest known observable systems, globular clusters; these age determinations will be enabled by sensitive spectroscopic observations which can provide accurate distances and chemical abundances for stars in Milky Way globulars;
- carrying out study of stellar oscillations through high signal/noise, high resolution spectroscopy, and determining the internal structure of stars other than the sun.

Most of these problems require not only increased collecting area, but the observation of large samples of objects. Some are feasible only if the development of 8-m class telescope is accompanied by the construction of advanced multi-object spectrographs capable of simultaneous observation of several hundred objects within fields of view of dimension $20'$ to $30'$.

New Science Enabled by Diffraction-Limited Imaging

The development of adaptive optics for use with 8-m optical/infrared telescopes will provide diffraction-limited images at near- and mid- infrared wavelengths, $\lambda \geq 1.6\ \mu$m by mid-decade, thereby improving image quality by nearly tenfold when compared with typical atmospheric seeing.

By reducing the *size* of a stellar image from the seeing-limit to the diffraction-limit of the telescope, faint point sources will stand out far more prominently against the background produced by night sky emission and by the thermal radiation emanating from the telescope itself. Not only will sensitivity to faint sources be improved, but the diffraction-limited images provided by adaptive optics will also 1) resolve objects in crowded, source-confused regions; and 2) reveal and resolve structures heretofore hidden from view within the seeing disk. *Examples* of the power of adaptive optics used in combination with large ground-based telescopes to *enable* attacks on new classes of problems include:

- determining the morphology, star-forming activity, and chemical composition of galaxies at their formation epoch, by means of high resolution imaging and spectroscopic studies in the red and near infrared spectral regions;
- determining the stellar content and mass distribution of the Galactic Center through imaging and spectroscopic studies of this optically-obscured, densely-populated region at 2.2 μm;
- determining the efficiency of star formation and constraining the initial mass function from infrared imaging and spectroscopic observations of obscured regions of highly-efficient star formation – analogs to the Orion cluster, where the stellar density may exceed 20,000 stars/pc^{-3}, and the mean separation between faint stars is $\leq 1''$.
- determining the structure, mineralogy, and gas content of solar-system size disks predicted to surround young, solar-type stars, thus providing astronomical constraints on the evolution of primordial solar nebulae. Pre-planetary disks are expected to have diameters $\sim$100 AU or $0.7''$ around the nearest young stars, and are thus hidden within the seeing disk of the bright parent object.
- obtaining images and spectra of massive planets and sub-stellar mass companions located within $1''$ of parent stars with ages 10 Myr and less, when such sub-stellar mass objects are most luminous;
- obtaining spectroscopic and imaging observations of planets within the solar system at angular resolutions $\sim 0.05''$, thereby enabling remote studies of surface mineralogy (Mars) and of atmospheric structure and composition (Jovian planets);

The gains offered by adaptive optics are potentially so great that we recommend that during the decade, all 8-m telescopes in the US be equipped with systems capable of *full adaptive corrections in the near-infrared.* Full corrections at *optical* wavelengths will involve more complex wavefront sensors and adaptive mirrors, and will likely be achieved only toward the end of the decade, following investment in a significant research and development program.

Expected Performance Gains

The quantitative gains expected from 8-m class telescopes depend upon the nature of the problem and the telescope performance. In Table 2, we summarize these gains for observations in which the signal/noise ratio of a given observation or the required observing time is limited a) by the flux of incoming photons from a source (for example, most high spectral resolution observations at optical wavelengths); and b) by the background emission from the night sky or the telescope (e.g. low resolution spectroscopy of galaxies; detection of excess mid-infrared emission from circumstellar disks surrounding young stars). We consider two cases

- that the observations are limited by atmospheric seeing as is the case for telescopes with no adaptive corrections for incoming wavefront distortions;
- that diffraction limited images are achieved; 8-m telescopes equipped with modest adaptive optics systems will deliver diffraction-limited imaging at wavelengths as short as 1.6 μm by mid-decade or before.

For photon-limited observations, the time required to reach a fixed S/N will be decreased by a factor of 4 for an 8-m compared to a 4-m diameter telescope. This gain will enable high resolution, high S/N spectroscopic studies of large samples of objects currently beyond the practical limits of 4-m class telescopes (e.g. observations of unadulterated atmospheric chemical compositions for globular cluster main sequence stars). For background-limited observations, the time required to reach a fixed S/N will again be decreased fourfold for telescopes lacking adaptive optics. This gain will, for example, enable the assembly of redshifts for large samples of galaxies at the limit of the observable universe ($z \geq 3$). With adaptive optics, the time required to reach a fixed S/N will be decreased by *16 times* for faint point sources observed against sky or

Table 2. GAINS WITH INCREASING TELESCOPE DIAMETER

	Seeing-Limited		*Diffraction-Limited*	
	Unresolved Source	Resolved Source	Unresolved Source	Resolved Source(pix)$^{-1}$
	Photon-Limited Observations			
S/N	D^1	D^1	D^1	D^0
1/time (fix S/N)	D^2	D^2	D^2	D^0
	Background-Limited Observations			
S/N	D^1	D^1	D^2	D^0
1/time (fix S/N)	D^2	D^2	D^4	D^0

telescope background. The gains for infrared photometric and spectroscopic studies (e.g. of faint stars or unresolved obscured galactic nuclei) will thus be spectacular.

Recommended Program for the 1990s

The scientific programs enabled by 8-m class telescopes equipped with adaptive optics make it certain that such facilities will be among the leading tools of research and discovery during the next decade. As noted earlier, US leadership in ground-based astronomy–a constant of international science since the beginning of the 20th century–is being challenged as never before. ***If US astronomy is to maintain its vitality and leadership, it is essential that a new generation of large telescopes be built during this next decade and made available to members of the US astronomical community.***

The response to the challenge of maintaining leadership in O/IR astronomy has thus far come from private institutions and state universities who have raised funds for, and in some cases started to construct 8-m class telescopes. These independent large telescope efforts include (1) the nearly-completed Keck 10-m telescope (California Institute of Technology and the University of California), (2) the Columbus Project (University of Arizona, Ohio State University, and the government of Italy) to construct a pair of 8-m telescopes, (3) the Magellan Project (Carnegie Observatories, Johns Hopkins University, the University of Arizona) to construct an 8-m telescope in the southern hemisphere, (4) the Smithsonian Astrophysical Observatory and the University of Arizona project to replace the six 1.8m mirrors comprising the Multiple Mirror Telescope with a 6.5m monolith, and (5) the University of Texas, Pennsylvania State University program to construct an 8-m telescope specialized for spectroscopic studies. It is vital that these independently-funded telescopes be equipped initially and continue to be equipped with the most sophisticated instruments and detectors. This will require *federal* contributions over the next decade to complement the private and state funds already committed toward construction of these facilities. It is also vital to the health of US astronomy that the nation's astronomers have competitive access to uniquely capable ***national facilities*** of this size.

The O/IR panel therefore recommends a *coordinated program* to combine federal funds with state and private funds to ***build*** and ***instrument*** large (8-m class) US ground-based telescopes. This program should encourage innovative new developments (e.g. adaptive optics; advanced instrumentation) and the sharing of technologies and facilities to optimize the total national effort–independent consortium telescopes and national observatories–in optical and infrared astronomy. The key federal contributions to this program are:

- support ($120M) for the construction of ***a pair of 8-m telescopes,*** one each in the northern and southern hemisphere. The northern hemisphere telescope should be located on Mauna Kea, and be designed and operated to achieve optimized performance at infrared wavelengths. ***An infrared-optimized telescope located on Mauna Kea will provide US astronomers with a unique and powerful facility.*** Building and operating this telescope will require (1) that all telescope mirrors be silver-coated; (2) that procedures be developed to keep telescope mirrors dust-free in order to minimize thermal emission from optical surfaces; and (3) that the mirror be a monolith, with a polished surface of unsurpassed quality–sufficient to take full advantage of adaptive optics technology which promises diffraction-limited images at wavelengths 1.6 μm and longward by mid-decade. By demanding the lowest possible telescope emissivity and highest mirror quality, the national IR-optimized telescope will take full advantage of the superb infrared transmission and image stability of the Mauna Kea site. The combination of diffraction-limited imaging and high sensitivity will make the IRO uniquely capable of carrying out the most demanding observations of forming galaxies, stars and planetary systems.

The southern hemisphere 8-m national optical/infrared telescope *should be a twin of the northern hemisphere telescope* in order to achieve the cost savings which derive from commonalty of design. It will provide US astronomers with the ability to observe the many objects (e.g. the Magellanic Clouds, the center of the Milky Way) best studied from the southern hemisphere. The need for access to the southern skies is particularly pressing in the era of the Great Observatories, which can observe astronomical objects over the complete celestial sphere; without national access to a southern hemisphere 8-m class telescope, US astronomers will be at an enormous disadvantage in characterizing new phenomena discovered by these space-based facilities. The O/IR panel recommends that *initially* the southern hemisphere 8-m telescope mirrors be coated with aluminum in order to optimize performance at optical and near-ultraviolet wavelengths. The southern hemisphere 8-m telescope will thus complement the infrared-optimized northern hemisphere facility, and will enable astronomers to carry out a number of important scientific problems (e.g. studies of quasi-stellar object (QSO) absorption spectra) for with the IRO is unsuitable. At some point, it may be desirable to coat the optics with silver in order that the southern hemisphere 8-m be able to carry out sensitive infrared observations of objects accessible solely from the southern hemisphere.

- support ($10M - $15M) for immediate development and deployment (on all new generation US telescopes of diameter 4-m and larger) of wavefront sensors and adaptive mirrors capable of providing full adaptive corrections at near-infrared wavelengths. This program is critical, not only for achieving gains in angular resolution and sensitivity, but to *enable* or greatly simplify development of advanced auxiliary instrumentation for large telescopes through reduction of the image size (for unresolved sources) from the seeing-limit to the diffraction-limit.
- support ($40M-$50M) for developing and building advanced auxiliary instruments required both for the new generation of large O/IR telescopes. Instruments for these new generation telescopes will be large in scale, technically sophisticated, and in many cases far more expensive than analogous auxiliary devices on extant 4-m class telescopes. The larger instruments for these telescopes may cost in excess of $5M. Both the pair of national 8-m telescopes and the independent 8-m projects include in their budgets funds for an initial complement of basic instruments (e.g. optical and infrared cameras; faint object spectrographs). Our recommendation is directed at providing the funds necessary for the development and construction of *advanced instrumentation,* both for the pair of national 8-m telescopes *and for the 8-m telescopes under construction by private/state consortia.* Examples of such instruments include

    - multi-object spectrographs capable of obtaining spectra of several hundred galaxies or stars simultaneously;

    - cryogenic echelle spectrographs (which will take advantage of advances in IR array technology in order to provide 10,000 fold improvements in sensitivity over currently availably high spectral resolution devices).

The requirement over the decade for advanced instrumentation for these new facilities will necessitate federal funding at a rate twice that of the current annual NSF expenditures for O/IR instrumentation.

The recommended decadal investment in O/IR instruments for large telescopes *presupposes* a vigorous program to develop and distribute advanced optical and infrared array detectors (see below). Such a program is a vital prerequisite for this recommended instrumentation program and for effective use of large telescopes throughout the community.

The availability of funding to construct advanced instruments is a key element of our recommended coordinated program aimed at combining federal funding with state and private resources to fully develop the facilities and instruments required for a competitive program in ground-based optical/infrared astronomy during the 1990s. Our program recognizes the essential role played by the private telescopes in providing the US with the complement of large telescopes required to retain its competitive position in world astronomy: private and state resources exceeding $150M have already been invested in or will be committed to the construction of 8-m class telescopes. Funding for advanced instrumentation at the recommended level is required in order that these facilities, as well as the national 8-m telescopes be able to carry out competitive frontier observations throughout the decade.

Our recommended funding level assumes that very expensive or specialized instruments will not in general be replicated. In many cases, several teams of scientists from throughout the community may propose competitive instrumental approaches, only one of which may be funded. If the winning team proposes to locate a unique instrument at an "independent" observatory, national access should be made available either through mutually agreeable financial arrangements or through exchange of telescope time.

RECOMMENDATIONS OF THE PANEL: MEDIUM SCALE PROGRAMS

Priority 1: A Coordinated Program For High Angular Resolution

Background

During the 1980s, astronomers worldwide devoted considerable effort to developing ways to increase the angular resolution of ground-based telescopes:

- improving the local seeing introduced in the immediate telescope environment; through careful control of the thermal environment of the dome, the size of the seeing disk has been reduced from $\sim 1''$ to $\sim 0.5''$ at superior sites;
- controlling primary mirror figure and telescope focus through active corrections applied on timescales of minutes to hours; the European Southern Observatory (ESO) NTT has achieved $0.3''$ images at optical wavelengths using this technique;
- correcting for instantaneous ($\tau \leq 0.1$ sec) distortions in the incoming wavefront by use of wavefront sensors and adaptive mirrors; use of adaptive optics at the ESO NTT has produced near-infrared (2.2 μm) images in which a significant fraction of the light is concentrated in a diffraction-limited core of diameter $\sim 0.14''$.

Our recommended program for the development of "new generation" large O/IR telescopes assumes building, telescope, and instrument designs that incorporate all these techniques. As a result, we confidently anticipate that this new generation of large telescopes will produce diffraction-limited images at $\lambda \geq 1.6$ μm, and will thus routinely provide angular resolutions of $0.05''$ at 1.6 μm and $0.2''$ at 10 μm.

In order to improve angular resolution beyond this limit requires (1) extending diffraction-limited observations to wavelengths $\lambda \leq 1.6$ μm, (2) constructing larger telescopes, and (3) the development of interferometric arrays.

Experimenters are now working on techniques to extend the capability for full adaptive corrections to optical wavelengths. This effort will require development of sophisticated wavefront sensors, complex adaptive mirrors and laser reference stars. When available late in the decade and used in conjunction with 8-m telescopes, these systems will provide diffraction-limited images of diameter $0.02''$ at 0.55 μm, 3 times the corresponding angular resolution at 1.6 μm.

The design of single optical/infrared telescopes with apertures much larger than 8-m (perhaps 30 m to 50 m) now seems feasible given the advances in mirror technology and O/IR telescope design made during the 1980s. Such telescopes would provide diffraction-limited images of size $\sim 0.01''$ at 1.6 μm and $0.003''$ at 0.55 μm with consequent gains in both angular resolution *and* sensitivity to faint unresolved sources.

The 1980s also witnessed major advances in overcoming the difficulties inherent in ground-based interferometric imaging at optical/infrared wavelengths. Following the French astronomers at CERGA, and the experience gained in the United States by the astronomers supported by the United States Navy, experimentalists are now confident that an optical/infrared interferometric array comprised of $\sim$5 elements distributed along baselines ranging up to least $\sim$200m can be built during this decade. Such an array could provide images of size $\sim 0.002''$ at 1.6 μm and $0.0007''$ at 0.55 μm and sensitivity proportional to the aggregate collecting area of the telescopes comprising the array.

The prospect of increasing the angular resolution of optical/infrared observations by 2 orders of magnitude over the span of a decade would be nothing short of revolutionary. We therefore strongly urge a coordinated program for development of high angular resolution astronomy during the next decade. This program involves

(1) continued development of adaptive optics to extend the reduction in image size gained from application of this technique from infrared to optical wavelengths; (2) engineering studies leading to the design of ultra-large, adaptively-corrected single aperture telescopes; (3) vigorous support of ground-based O/IR interferometry; and (4) engineering studies leading to the design of an optical/infrared analog of the Very Large Array.

New Science Enabled by High Angular Resolution Observations

By extending full adaptive corrections from the infrared to optical wavelengths, 8-m telescopes will deliver diffraction-limited images of size $\sim 0.02''$ at 0.55 μm. Thus, in some applications, these telescopes will provide 4 times the angular resolution and 16 times the sensitivity of HST at optical wavelengths. These gains in angular resolution and sensitivity will be particularly critical to:

- (1) study of the stellar populations and source distribution in the nuclear bulge and star-forming regions in nearby galaxies;
- (2) detection of Cepheid variables and M supergiants and other standard candles against the arm and disk light of spiral galaxies;
- (3) detection and spectroscopy of globular clusters located in the halos of distant elliptical and spiral galaxies;
- (4) probing the planet-forming regions of primordial solar nebulae associated with young stars to distances as close as 3 AU from the surface of the parent solar-type;
- (5) imaging solar system bodies with a resolution of $0.02''$ (75 km at the distance of Jupiter).

Problems (1) to (3) are representative of a class of measurements which require gains in both sensitivity and angular resolution in order to detect and analyze faint sources in crowded regions viewed against the sky background. Problems (4) and (5) illustrate the sheer power of imaging at $0.002''$ resolution.

The next threshold in angular resolution that promises a dramatic increases in the range of accessible astronomical phenomena occurs at $0.001''$ (1 mas) or 20 times the resolution anticipated for 8-m class telescopes at optical wavelengths once full adaptive corrections are available. With instruments capable of delivering 1 mas resolution at O/IR wavelengths, astronomers will for the first time be able to:

- obtain detailed images at a resolution of 1 pc of the narrow-line emission regions of active galactic nuclei and crude structural information about the broad emission-line region of AGNs;
- image accretion disks in close binaries at resolutions of 0.1 AU
- image expanding envelopes around late-type stars with resolutions of 0.1 to 1 AU;
- image pulsating stars and monitor changes in their angular diameters;
- image planet-forming disks, jets and winds associated with young solar-type stars with resolutions ~ 0.1 AU;
- image the photospheres of nearby main sequence stars and more distant giant and supergiant stars;

Recommended Program for the 1990s

At present, efforts to develop high angular resolution techniques at optical and infrared wavelengths in the United States lag behind comparable efforts in Europe. The scientific opportunities that derive from sensitive high angular resolution O/IR imaging are so compelling that we urge strong support of a program aimed at positioning the US astronomical community to assume leadership in this field by the beginning of the next decade. The major elements of this program include:

- vigorous support ($10-$15M) of efforts to extend the wavelength range for full adaptive corrections from the near-infrared to optical wavelengths. This funding level *assumes* the prior commitment of $10M-$15M to build adaptive optics systems for full wavefront correction in the near infrared–already included as an integral part of our recommended program to construct and instrument the new generation of large O/IR telescopes. Full wavefront correction at optical wavelengths requires much more complex wavefront sensors, adaptive mirrors involving thousands of actuators, and an artificial "laser star" to provide the reference for measuring wavefront correction. reference source (a "laser star") must be developed in order to measure wavefront distortions. Full adaptive corrections extending to optical wavelengths also makes it attractive to design large, single-aperture telescopes capable of enormous gains in sensitivity for background-limited problems. Investment in a program to develop adaptive optics is critical *not only* to achieving diffraction-limited imaging at infrared and optical wavelengths with large single-aperture telescopes, but to enabling *high sensitivity* interferometric imaging, particularly at optical wavelengths. Without adaptive optics, the largest telescope apertures that can be used effectively in interferometric arrays are comparable to the coherence length (r_0) for an incoming wavefront: 1m to 2 m at near-infrared wavelengths, but only 0.1 m to 0.2 m at optical wavelengths (see Table 1). With adaptive optics, the full aperture of each interferometer element can be employed.

- support ($2M) for engineering efforts aimed at designing ultra-large ($D \geq 30$ m), adaptively-corrected telescopes capable of providing dramatic gains in sensitivity and threefold increase in angular resolution.
- immediate support ($10-15M) for a few, well-focused university-based efforts to build and operate pilot interferometers involving at least 3 small telescopes (diameter ≤ 1 m) located along variable baselines extending to between 50 m and 100 m. The primary goal of these interferometers is to develop efficient techniques to enable successful optical/IR interferometry on a routine basis (e.g. fringe tracking, beam combination, phase closure). Investment in these efforts will not only hasten development of these techniques, but will build the necessary infrastructure of graduate students and faculty to drive further development of interferometry. Despite their modest size and pioneering nature, we can anticipate important scientific returns in several areas, including:
    - measurement of fundamental astrophysical quantities such as stellar masses, luminosities and diameters;
    - imaging of the surfaces of giant and supergiant stars, and of dust envelopes surrounding evolved stars;
- support ($5M) of efforts to develop infrared and optical interferometry with 8-m class telescopes located on fixed baselines; these efforts will provide the experience necessary to carry out interferometry with large adaptively-corrected array elements;
- support ($15M) by mid-decade of a university-based effort to develop a sensitive O/IR interferometer array. This array should be comprised of at least 3 and perhaps as many as 5 telescopes of diameter $\sim$2m located along continuously adjustable baselines of dimension ≥ 200 m. We can anticipate that such an interferometer will first take advantage of the more benign character of the atmosphere at longer wavelengths (greater correlation lengths, permitting the full use of apertures of size $\sim$2m, and longer correlation times, permitting fainter sources to be used to determine atmospheric phase) to provide ***high sensitivity near-infrared images*** at an angular resolution $\theta \sim 0.002''$–comparable to images achievable with VLBI techniques at cm-wavelengths. Later in the decade, when full adaptive corrections are possible at optical wavelengths, the recommended interferometer will be capable of making sensitive images in this wavelength regime as well;
- support ($10M) before the end of the decade to begin planning a national O/IR array. The program advocated above will provide the basis for planning an advanced optical/IR array to be constructed as a national facility between 2000 and 2010. The array will probably comprise a considerable number ($\gg$ 10) of apertures with a collecting area of ≥ 100 m^2.

This approach is modeled on the highly successful strategy which led to the development of millimeter-wave interferometry by university groups during the 1980s, and which promises to culminate in the construction of a national mm-wave array during the 1990s. Our recommended program in O/IR interferometry would continue the wise federal strategy which has gained world leadership for the US in high angular resolution astronomy – starting with the VLA, and VLBA and continuing through the development of mm-interferometry –***by providing the basis for beginning construction of a national O/IR Very Large Array at the beginning of the next century.***

Priority 2: A New Generation Of 4-m Class Telescopes

Background

Ground-based optical and infrared observations are central to developing a deep understanding of astrophysical systems and placing exotic phenomena discovered at other wavelengths in the context of the "known." While ***discovery*** most often follows the opening of new frontiers in wavelength, sensitivity or angular resolution, ***understanding*** usually requires a great deal of detective work by large numbers of scientists with access to appropriate investigative tools. As we enter the 1990s, the basic "tool" of *understanding* is an optical/infrared telescope of diameter ~4 meters. As we enter the 1990s, the number of observing hours available on 4-m class telescopes is woefully insufficient when compared with the time required to carry out the basic observational studies which lead to understanding. As a result, only a small fraction of the investigations thought to be most pressing can be granted telescope time, and often in quantity so minute as to preclude exploratory investigations or the assembly of databases adequate to ensure proper interpretation. The pressure will only increase as discoveries made with the Great Observatories place even greater demands on extant facilities for supporting and follow-up observations.

Examples of the range of important scientific programs requiring extensive time on 4-m class telescopes include:

- characterizing the physical properties of sources discovered at other wavelengths (e.g. by Einstein, IRAS, ROSAT, GRO, AXAF, SIRTF) through imaging and spectroscopy;
- monitoring surface and chromospheric activity on solar-like stars;
- determining the interior structures of other stars from long-term spectroscopic monitoring programs designed to characterize stellar oscillation modes;
- searching for other planetary systems and sub-solar mass objects by means of long-term radial velocity studies of large samples of stars;
- carrying out synoptic spectroscopic and photometric studies of supernovae in external galaxies and active galactic nuclei;
- mapping the large scale structure of the universe out to $z \sim 0.1$ by determining the redshifts of 1 million galaxies;
- mapping the large scale structure of the universe out to much larger distances by determining redshifts of galaxies in carefully selected "pencil beams";

Recommended Program for the 1990s

The technological advances which enable the construction of 8-m class O/IR telescopes have greatly reduced the size, weight, and cost of 4-m telescopes, while enhancing their image quality and operational efficiency; the superb image quality obtained with the ESO New Technology Telescope attests to the potential of these new generation facilities. As a result of these advances, powerful facilities of this class can be built by individual universities or small consortia of institutions.

The O/IR panel recommends a program to build at least 4 new generation telescopes of aperture ~ 4 meters during the 1990s. Federal funds ($30 M) would be used in combination with state and private monies in order to construct these telescopes. The most urgent community need is to begin immediate construction of two general purpose 4-m class telescopes–one located in each hemisphere–to support and complement the NASA Great Observatories. University involvement in operation and management of these facilities will have the added benefit of providing opportunities for deep student involvement in both carrying out long term and/or exploratory programs and in developing novel instrumentation.

Our recommended program to construct four new generation 4-m class telescopes during the next decade is the *minimum* required to meet the most pressing needs of the community. The O/IR panel wishes to encourage in the strongest terms imaginative arrangements to build *additional* new generation 4-m class telescopes by combining state and private funds with modest levels of federal support.

A variety of models for siting and operating telescopes of this size have been suggested and many are viable. However, the economics of building and operating university telescopes of this scale requires that they be located at *a few* already developed excellent sites, thus saving development costs through sharing of roads, dormitories and support personnel.

The panel is particularly impressed by the advantages of arrangements whereby the facility is constructed with private and/or state funds on an NOAO site, while operation costs are assumed by increments to the NOAO operating budget from federal sources. This arrangement provides telescope time for (1) astronomers on the faculties of the institution(s) responsible for raising capital costs; (2) time for astronomers throughout the community who compete for access to the facility on the basis of peer-reviewed scientific proposals; and 3) takes full advantage of the nation's investment in the NOAO support infrastructure, which can provide the resources for economical, efficient and "user-friendly" operation. Such arrangements also provide the basis for continued economical operation of the existing 4-m and smaller telescopes at KPNO and CTIO – which the O/IR panel regards as critical to the scientific vitality of the US astronomical community.

RECOMMENDATIONS OF THE PANEL: SMALL SCALE PROGRAMS

Priority 1: Near-IR And Optical All-Sky Surveys

All sky surveys to fixed flux levels (e.g. the National Geographic/Palomar Observatory photographic sky survey and the recently completed IRAS infrared survey) are critical to efforts aimed at understanding the distribution of objects comprising the observable universe. Such surveys are essential because they provide *complete* pictures of the sky, unbiased by selection effects. Well-designed surveys provide the basis for vital scientific research long after their completion. For example, the galaxy redshift programs of the past decade which revealed the web-like distribution of galaxies in the universe were designed from catalogs of galaxies constructed from the first Palomar Observatory sky survey (POSS)–completed nearly 40 years ago. Advances in optical and infrared detector technology have made it possible to carry out deep all-sky digital surveys with high photometric accuracy. These surveys promise to provide fundamental databases for cataloging the distribution and brightnesses of galactic and extragalactic objects – the ultimate basis for designing a wide range of scientific programs for ground-based and space-based telescopes. *The O/IR panel recommends the completion of digital all sky surveys at (1) near-infrared, and (2) optical wavelengths before the end of the decade.*

A Near-Infrared All Sky Survey

An all sky survey at near-IR wavelengths

- can provide a complete picture of the structure of the Galaxy and the universe unhampered by the opaque dust which obscures optical views through the plane of the Milky Way.
- can probe the interior regions of optically-opaque star-forming regions,
- can locate radiation emitted by the coldest stars–objects which dominate the observable mass of our own and other galaxies.

A new, near-infrared survey can be carried out in a scanning mode (analogous to the IRAS survey)over the next five years on small telescopes (diameter ~1 meter) using moderate-size infrared arrays. Such a survey would have a limiting magnitude of 14 at K (2.2 μm) – nearly 50,000 times fainter than the faintest source catalogued in the original Two Micron Sky Survey. The proposed infrared survey is urgently needed (1) for developing target lists and planning initial observing programs for the two major US infrared space missions of the 1990s: SIRTF, and the NICMOS imaging camera/multi-object spectrograph on HST; and (2) to act as the near-IR analog of the POSS for guiding development of observing programs for the 8-m IR-optimized telescope. A survey of this sensitivity will also enable a wide range of investigations in its own right. These include

- carrying out a census of galaxies *uniformly around the sky* , thus sampling the nearby universe and its gravitational potential field to redshifts z~0.05. We note that the "Great Attractor" which has been invoked to account for asymmetries in the redshifts of galaxies out to distances of ~100 Mpc appears to be located along a direction which is obscured from view at optical wavelengths by dust in the plane of the Milky Way;
- using the observed infrared brightnesses of spiral galaxies derived from the survey, along with neutral hydrogen line profiles, to determine accurate distances to large numbers of galaxies;
- probing the structure of the Milky Way galaxy by using K and M giants and infrared-bright asymptotic giant branch stars;
- providing deep maps of star-forming regions in Gould's Belt and in the Perseus, Sagittarius, and Carina arms of the Milky Way;
- providing the most sensitive means yet proposed (in terms of volume searched) to locate elusive sub-stellar mass objects ("brown dwarfs").

The survey must be carried out with two telescopes, one located in the Northern hemisphere, the other in the South. The estimated cost to build the required telescopes and cameras for the all-sky near-IR survey is $6M.

We recommend that the survey data be archived and made widely available to the international community of astronomers by using procedures analogous to those already developed at NASA's Image

Processing and Analysis Center (IPAC) which has provided exemplary service to the community in archiving and disseminating the IRAS database.

All-Sky Optical Survey

Since the invention of photography, astronomers have used deep sky images as their primary tool to learn about the morphology and distribution of objects which comprise the observable universe. The most important of these surveys has been the Palomar Observatory Sky Survey (POSS), completed in the early 1950s. This photographic survey and its successor (the deep Palomar II survey), and others like them in the southern hemisphere have been the mainstays of much astronomical research – providing the basis for identifying galaxies and clusters of galaxies, and cosmic sources of gamma-rays, x-rays, IR and radio radiation.

With the advent of large-format, sensitive digital detectors (e.g. 2048x2048 CCD arrays) it is now possible to replace photographic surveys by surveys that are both digital and well calibrated photometrically. We propose a survey aimed at obtaining simultaneous images of the sky at B (0.44 μm) and R (0.65 μm) which provide S/N = 10 for objects of B=23 and R=22 magnitude at a spatial resolution of $1''$/pixel. It is desirable to complete a survey of both celestial hemispheres within 5 years.

Such a digital survey will provide:

- a uniform sample of galaxies to 20th magnitude (15 million galaxies at galactic latitudes, $b \geq 30^{\circ}$); this catalog will provide the basis for designing deep redshift surveys aimed at mapping the three-dimensional structure of the universe out to large distances;
- select clusters of galaxies to redshifts near unity (at $z = 1$, the 10th brightest galaxy in a cluster is B $\sim$21 mag);
- obtain accurate photometry for brighter galaxies and stars, allowing the construction of photometrically uniform samples and color-selected samples;
- locate faint optical counterparts for radio, x-ray, gamma-ray, and infrared sources.

The survey requires a dedicated 1-m class telescope of conventional design. After completion of the initial all-sky survey, it will be possible to use the same equipment to carry out 1) deeper surveys in selected regions; 2) surveys with higher angular resolution in order to achieve high photometric accuracy for stellar objects in our own galaxy.

We recommend that the optical all-sky survey results be archived and made available to the international community of astronomers using the procedures established for the dissemination of IRAS and HST data at IPAC and STScI.

The estimated cost of the all-sky optical survey is between \$3M and \$5M depending upon whether extant facilities can be used or new telescopes must be constructed.

The panel wishes to note that the recommended infrared and optical all sky surveys are deemed the most pressing and important representatives of a much larger class of more specialized surveys (e.g. narrow-band imaging surveys at Hα and H_2 enabled by modern optical and infrared detector technology). It is thus essential that these two recommended surveys be designed with a clear goal of developing a community-accessible infrastructure for the reduction, analysis, archiving and distribution of databases assembled by more specialized surveys. It is these functions which are most costly over the long term, and yet most vital for ensuring the production of a uniform, well-understood and well-used database. It seems wise to make use of the current community investment in the facilities and scientific expertise assembled at IPAC and STScI to support such specialized surveys.

Priority 2: A National Astrometric Facility

Ground-based astrometry has made dramatic gains over the past decade, as a result of applying modern CCD detectors, image analysis techniques and innovative new instrumentation to astrometric measurements. Several groups have demonstrated accuracies in position determinations of 1 milliarcsecond (1 mas) or greater – a gain of 5 or more when compared to previous measurements.

Although this accuracy offers the potential to determine and calibrate fundamental stellar parameters, the number of stars for which such measurements are needed far exceeds the capabilities of existing astrometric programs. Moreover, ground-based and space-based programs are identifying many objects of interest with undetermined physical properties. Measurement of the parallax and proper motion of these objects is often a necessary prerequisite to further study.

Furthermore, the internal positional accuracy of images obtained with new space-based facilities (and by the mid-1990s, large ground-based telescopes equipped with adaptive optics) exceeds the accuracy of the optical reference frame (~50 mas) and the accuracy of the intercomparison of the optical and radio reference frames (~300 mas). Transferring coordinates between reference frames, particularly at radio and optical wavelengths, is critical to enabling the precise registration of images required for detailed multi-wavelength studies of spatially-resolved systems.

Finally, the search for planets, brown dwarfs and other underluminous objects must be undertaken over several decades and require both instrumental stability and long-term commitment of institutional resources to ensure their success.

The importance of these three classes of programs, the specialized nature of the instrumentation, the requirement for long-term stability and the need to supply the astronomical community with fundamental data lead the O/IR panel to *recommend the construction of a special purpose, dedicated 1.5m telescope and ancillary instrumentation. We urge that this facility be operated as a national observatory.*

The recommended *National Astrometric Facility* should be funded and operated in a manner which permits both rapid response to targets of opportunity (e.g. orbit determinations for solar system objects), and long-term commitment to programs requiring *decades* of observation (e.g. searches for planetary systems). It should be scheduled in response to proposals arising from the astronomical community. The National Astrometric Facility should also provide a test bed for development of innovative astrometric instrumentation and techniques.

The panel estimates that the construction and initial instrumentation cost of such a facility to be $5M. The first such facility should be built in the northern hemisphere at a first class site. In the long-term, a twin facility should be developed for the southern hemisphere.

RECOMMENDATIONS OF THE PANEL: INFRASTRUCTURE ISSUES

Develop, Purchase and Distribute Optical CCDs and Infrared Arrays

The development of optical charge coupled devices (CCDs) and near infrared arrays has revolutionized optical/infrared astronomy. At optical wavelengths, CCDs provide an order of magnitude improvement in sensitivity for most applications over the previous generation of detectors, and provide major improvements as well in geometric and photometric stability. With current noise levels approaching a few electrons rms, and quantum efficiencies near 80 percent, they are very nearly ideal detectors. Infrared arrays are less mature but no less revolutionary in their impact on the field. Near-infrared arrays (HgCdTe and InSb) have *enabled* infrared sensitive imaging and two-dimensional spectroscopy for the first time.

Our recommended program for the 1990s assumes as a prerequisite, adequate funding for the development and distribution of advanced panoramic detectors. Without this investment, it will be impossible to achieve the full potential of new generation, large telescopes. We outline below the elements of a national program to develop, purchase and distribute large format CCDs and infrared arrays.

Optical CCDs

The past decade has seen very rapid development, but still *unsatisfactory general availability* of large CCDs suitable for astronomy. Thanks to a fairly major NSF/NASA effort, the TI 800x800 chips developed for the Wide Field/Planetary Camera on HST have been distributed widely to the community. However, these devices have been far surpassed in performance by newer chips. Moreover, they are not well suited in overall dimension or pixel size to the new generation of large, 8-m class telescopes. *The O/IR Panel strongly recommends a program developing CCD detectors optimized for performance on large telescopes, purchasing them in sufficient quantity, and distributing them competitively to the astronomical community.*

It is essential that all large telescopes be equipped with CCDs if they are to achieve their full potential. To achieve this goal, the Panel has identified the following actions that need to be taken as soon as possible:

- A coordinated purchase of a particular CCD design in quantity and volume sufficient to interest commercial vendors in providing the fabrication and cosmetic quality required for astronomical detectors.

- A coordinated development program to understand the advanced CCD technologies needed for the next generation of astronomical devices and to develop those technologies so that they can be included in commercially available devices.

A wide variety of instrumentation needs on telescopes of all aperture sizes can be addressed by a single CCD design with the following characteristics.

- Pixel size determined by existing optical systems: As has been demonstrated by the NSF/NASA TI 800x800 CCD distribution, most existing optical systems are well matched by a 15 micron pixel size. Instrumentation on 8-m telescopes requires pixel sizes nearer 30 microns. Through the technique of on-chip binning, the same CCD can satisfy both requirements in most applications.
- Large Format: Wide field imaging and spectroscopy require minimum array sizes of 4096x4096 15-micron pixels, and many advanced applications require mosaiced-arrays of such devices.
- Charge Transfer Efficiency At Low Light Levels: The ideal device would require 99 percent collection efficiency at the far corner of the device, or better than 0.999992 efficiency per transfer assuming a three-phase, quadrant readout design.
- Low Noise: Amplifiers with rms noise levels of $\sim$4 electrons at rates of 50,000 pixels per second are now common. Requiring non-destructive readout with a few electrons rms seems feasible.
- Wide Wavelength Coverage: CCD detectors, by virtue of their native silicon photoconductor response, typically have quantum efficiencies of 60-80 percent in the green and red spectral regions. The response in the blue and ultraviolet is another matter. All approaches to maximizing blue response require that the device be *thinned* – that is, made thin enough so that light can strike the back side, away from the gate circuitry which is opaque to blue light. The alternative, covering the front surface with a photon energy down-converter, does not offer the tremendous gains offered by thinning.

While this CCD design is good, and its general availability requirement is urgent, it is not perfect. Research is needed in many areas, including flashgate technologies to improve the blue quantum efficiency of thin devices, anti-reflection coatings to optimize response in particular wavelength regions, mosaic technologies for combining devices, amplifier design for the minimization of noise, and gate structures to allow operation at warmer temperatures. A coordinated program to design, acquire, and test CCDs is needed to bring these advances from the laboratory to the telescope.

A major obstacle to concentrating effort on producing large format CCDs optimized for astronomical use has been the piecemeal purchasing patterns which are a result of the *lack of a concerted funding effort in this very critical area.* It is clear that expenditures small compared to the capital outlay for a large telescope would have an enormous impact on the availability of these crucial detectors. The Panel estimates that expenditure of $5M for the chip design discussed above would provide the few hundred devices required by the community. The cost of the research efforts and a second coordinated purchase of CCDs later in the decade would require an additional $5M. It is important to emphasize that the total $10M *is not* to be spent at $1M/year; it is critical that the first installment of $5M be provided immediately so that the large format chips be purchased and available for timely installation on the new generation 4-m and 8-m telescopes.

Infrared Arrays: The Future for the 1-5 μm Region

The NICMOS (Near Infrared Camera, Multi-Object Spectrograph) program has provided powerful 256x256 pixel arrays. Imaging and spectroscopy would benefit enormously from the production of larger arrays. InSb and HgCdTe arrays of dimension 512x512 seem technically feasible, but at present there is no support to develop larger successors to the NICMOS arrays. *We recommend a program to develop, purchase and distribute larger near-infrared arrays.*

Prior to a large-scale purchase, it is essential to carry out additional research and development aimed at providing better uniformity and broader wavelength response for these detector materials. It would also be extremely valuable to invest in the development of array designs that enable *moisaicing* of arrays.

Infrared Arrays: The Future for Mid-Infrared Arrays

The very high sky and telescope background at $\lambda \sim 10$ μm produce enormous background fluxes ($\geq 10^9$ photons/s) which have made array implementation very difficult. Two strategies have been attempted:

- read out the detector as fast as possible (before the wells fill), or
- increase the well-depth by increasing the detector bias

Neither provides per pixel performance on par with the best achievable with single detectors. Because the problems are daunting, fewer groups are working at these wavelengths, and moreover, the spinoff from

SIRTF-driven research is minimal because the background levels for this cooled telescope in space are very much lower than for ground-based applications.

The development of these detectors is *essential* if we are to take advantage of the dramatic gains in mid-IR sensitivity and angular resolution enabled by diffraction-limited 8-m IR/optimized telescopes; these telescopes will provide ~10 times the angular resolution of SIRTF in the 5-20 μm regime. *We recommend a program to develop sensitive, low-noise mid-IR array detectors for use on ground-based telescopes.* The panel notes that:

- good detector materials for mid-IR arrays exist: Si BIB detectors provide good quantum efficiency from 5 μm to 28 μm;
- the need for large well-depth (to accommodate high background fluxes) necessitates care in the design of the readout multiplexer; current devices may have unit cells which are too small to provide the needed large capacitances;
- It seems plausible to produce small mid-IR arrays (32x32 or 64x64 pixels) in the near term. To produce larger arrays would appear to require fundamental design work.

It is essential to fund several groups to work with industrial firms to develop and test detectors of astronomical use. However, to induce development of advanced technology arrays will require significant investments.

The O/IR panel recommends a total investment of ~ \$20M over the next decade in order to enable development, and later purchase, of the near- and mid-IR arrays that are so critical to achieving efficient returns from the new generation of large telescopes.

A Program to Support Large Optics Technology

Fabrication and Polishing of Large Mirrors

The coming decade is one of great promise for ground-based O/IR astronomy. A new generation of large telescopes is planned which, if built, will quadruple presently available light gathering power. Adaptive Optics hold the promise of diffraction-limited imaging by these telescopes, and offer more than an order of magnitude gain in angular resolution. *The key to these advances is the successful production of a number of primary mirrors 8-m in diameter–larger than any in existence.*

The fabrication of optics for these telescopes presents an enormous challenge. Methods have now been demonstrated on an intermediate scale for casting rigid glass honeycomb blanks. New techniques have been developed for polishing aspheric surfaces to the extremely high accuracies now required to match image quality at the best sites. All planned telescopes other than the Keck telescope will use these large monolithic mirrors.

As we enter the 1990s, construction of the first facility in the world for casting and polishing 8-m mirrors is nearing completion at the University of Arizona Mirror Lab. There still remains the task of proving the casting and polishing technology at the full size of the 8-m mirrors, and the production of six such mirrors during the decade. *The O/IR panel recommends continued support of the UAML at a rate of* ~ \$2M/yr throughout the decade.

Fabrication and Polishing of Specialized Optics; Coatings

The full potential of new telescopes will be realized only if they are equipped with excellent instruments. The best designs call for optical elements beyond present optical fabrication capability. *The O/IR panel wishes to encourage the funding* (\$500K/yr) of a coordinated effort involving university and private groups along with the NOAO to develop the technology for polishing difficult aspheric surfaces. It will also be necessary to invest in efforts aimed at developing efficient anti-reflection coatings and depositing them uniformly on large optical elements, along with efficient and durable reflective coatings aimed at minimizing telescope emissivity.

Toward a New Generation of Large Filled Aperture Telescopes

While much activity during the next decade will be devoted to the construction of 8-m class instruments and to the development of ground-based interferometry involving multiple small (~2-m class) telescopes, it would be wise as well to invest effort in developing the technology and encouraging imaginative approaches for construction of the next generation of large, single aperture telescopes.

One possible design for a 32-m class O/IR telescope is based on the mechanical structure of a radio telescope. In this concept, the dish is tiled with small polished glass segments, whose position would be rapidly adjusted to maintain diffraction-limited imaging, compensating not only for gravitational flexure as the telescope is moved, but also for wavefront aberrations caused by the atmosphere. To keep down fabrication cost, and to simplify alignment, the primary surface would be spherical (similar to the Arecibo telescope). To achieve good images, large and aspheric secondary and tertiary mirrors are required. New techniques for polishing large 8-m primaries for the telescopes of the 1990s appear extendable to these requirements.

Fundamental to the utility of large single apertures is the development of adaptive optics: the advantage of diffraction-limited imaging increases very rapidly with aperture. It follows that a very big telescope tailored for adaptive optics would be a very powerful tool. We can be fairly certain than a 32-m dish could be controlled to image much of the sky to the diffraction limit at 2.2 μm with the light from field stars. If the technology for sensing atmospheric wavefront errors from artificial (laser) stars is perfected, then diffraction-limited imaging over the whole sky will be possible at optical wavelengths. The corresponding resolution of $0.004''$ with all the light from a 32-m aperture focused into an image this small would constitute an extraordinary advance in astronomy.

We recommend funding at the rate of $\sim$ \$1M/yr over the next decade in order to support the design of large aperture telescopes, and to develop mirror fabrication and polishing technology required to enable the construction of such telescopes.

A Program to Archive and Disseminate Astronomical Databases

Modern astronomical images and spectra are now obtained almost exclusively in digital form. The O/IR panel believes that it is important to develop archives of coherent data sets *so the community of astronomers can derive maximum benefit from these data now and in the future.*

The value of archived data is amply illustrated by the following examples:

- the Palomar Observatory Sky Survey has proven an immensely valuable database both in its original photographic form, *and in its duplicate copies which have been disseminated widely in the astronomical community.* The survey has provided catalog and finding lists of a wide variety of celestial objects from galaxies, to H II regions, to Herbig-Haro objects. It has proven invaluable for selecting guide stars for the Hubble space telescope. In brief, it provides a paradigm for the wide-spread utility and scientific longevity of *astronomical surveys.*
- The databases from the HEAO and IRAS satellites have proven to be vital sources of astronomical research well after these satellites ceased taking data. It is also noteworthy that although the original science instrument teams for HEAO and IRAS are responsible for many of the exciting initial discoveries made with each satellite, *members of the scientific community working with these databases have been responsible for the bulk of the scientific return from these projects.* Moreover, wide involvement of the scientific community has led to better calibration and understanding of these databases as well as to richer scientific return. These databases provide a paradigm for the great value of community involvement in working with databases originally developed by teams of scientists working on a variety of key projects.

The O/IR panel recommends that funding be provided in order to ensure:

- that databases created by *surveys* (e.g. all sky digital surveys, catalogs of redshifts), and by *key projects* (long-term programs carried out by individual observers or teams of astronomers) be archived and following a 1 to 2 year period of exclusive use, be made available to the scientific community.
- that every observation taken on a large telescope in the US is catalogued and characterized and that the catalog of observations be made available to the scientific community.

The panel urges that the data be archived locally first, and then transmitted to more central archives such as those at IPAC and the STScI, and eventually to the NSSDC. The O/IR panel urges that *as a matter of policy* that the format of all archived data will be FITS (flexible image transport system).

The panel considered the possibility of archiving *all* data taken at large telescopes, but rejected the notion of universal archiving until procedures developed for surveys and key projects are developed, understood, optimized and costed.

A Program for Training New Instrumentalists

There is a major demand for talented young astronomers to design and build instrumentation for the next generation telescopes. The current shortage of trained instrumentalists will become even more acute unless the community can stimulate its students to take an active interest in state-of-the-art technology for astronomical observations. Training in the techniques of instrument creation has traditionally involved apprenticeship to an individual or group building and using new equipment. We recommend a three-level program aimed at providing such apprenticeships:

- *(1) Involve graduate students in instrumentation development at NOAO.*

The NOAO should initiate a program aimed at active involvement of advanced graduate students in the development of instrumentation at the national observatories. This program would provide support for students (and in some cases their advisors) in residence at the national observatory. During this time, such students would work closely with the team of scientists and engineers involved the design and construction of a major or innovative instrument. We also urge that NOAO seek frequent collaboration with university groups to develop instrumentation for the national observatories. Active collaboration with such groups would allow NOAO to tap and support the talent distributed throughout the university community, and to support students actively involved in these instrumentation efforts.

- *(2) Provide explicit support for graduate students at institutions developing instruments for moderate and large telescopes.*

At least 10 major university groups will be building and instrumenting moderate or large facilities during the 1990s. Students enrolled at these institutions have an unusual opportunity to become involved with the construction of frontier instrumentation.

However, all instrument large development projects are cost-constrained, and increasingly must meet demanding time schedules. These pressures act both to limit student involvement in large projects in favor of more experienced engineers and technicians, and to reduce their freedom to learn through making creative mistakes. Funding agencies must recognize these realities, and develop positive incentives to involve students in instrumentation development at these institutions. At the very least, the financial pressures which may prejudice graduate student support should be eliminated through initiation of an NSF program – analogous to the Research Experience for Undergraduates (REU) program – designed explicitly for support of graduate students involved in such projects. PIs for large instrument projects should be able to apply competitively for "IEG" (Instrumentation Experience for Graduate Students) grants. Furthermore, evidence of encouraging student involvement should be viewed as an important positive factor in the review process for instrumentation grants funded by NASA and the NSF.

- *(3) Provide support for graduate students at all institutions*

Universities with access to relatively small telescopes ($d \leq 1.5$m) can also play a critical role in training future instrumentalists if they are able to provide (1) steady access to telescopes with equipment *designed wholly or in substantial part by students;* (2) the infrastructure to enable student-built instruments to produce useful scientific results, including the availability of modern detectors, and adequate supplies of parts, tools, and test facilities; and (3) guidance by senior instrument designers who bear major responsibility for the student's career.

We recommend a new program for supporting operating costs and instrumentation development for small, University-operated telescopes. The program would provide funding for developing modern instruments for these telescopes, and for upgrading telescope control and data acquisition systems. The instruments need not be *unique,* frontier instruments. Rather, the request for funding should be judged on the basis of (1) potential for scientific return; (2) evidence of strong student involvement in the design, construction and use of the instrument; (3) the potential and track record of the senior mentor. This program would fill a gap between the NSF *Instructional Laboratory Improvement* grants and the traditional grants under the NSF Astronomy instrument program. These funds would be specifically targeted at support of creative programs aimed at *graduate training* of future instrumentalists.

We believe that initiation of this program would have a number of benefits. First and foremost, it would provide students with the involvement in a project over which she/he has primary control over design, construction and use. Second, it would result in the revitalization of a variety of local facilities, providing opportunities for student and faculty research on programs requiring imagination and a willingness to trade time for aperture. We cannot overemphasize the importance of giving students control of their own projects early-on in their formative years. Students involved in this program will be drawn to the pleasure of running a significant project from start to finish – and some will become the instrumental leaders of tomorrow. Funding of $\sim$ \$500K/yr over the next decade will be required.

UV-OPTICAL FROM SPACE PANEL

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