force for innovation and discovery in astronomical imaging.

Classical astronomy— for example, the search for new solar system objects and the classification of stars—is still largely conducted in the optical wavelength regime (400–700 nm). This has been the case, of course, since humans first imagined the constellations, noted the appearance of "wandering stars" (planets), and recorded the appearance of transient phenomena such as comets and novae. During the latter half of the twentieth century, however, a revolution in astronomical imaging took place (1). This relatively brief period in recorded history saw the development and rapid refinement of techniques for collecting and detecting electromagnetic radiation across a far broader wavelength range, from the radio through γ rays. Just as these techniques have reached maturation, astronomers have also developed the means to surmount apparently fundamental physical barriers placed on image quality, such as the distorting effects of refraction by Earth's atmosphere and diffraction by a single telescope of finite aperture. The accelerating pace of these innovations has resulted in deeper understanding of, and heightened appreciation for, both the rich diversity of astrophysical phenomena and the fundamental, unsolved mysteries of the cosmos.

OPENING THE WINDOWS: MULTIWAVELENGTH IMAGING

For most of us, our eyes provide our first, fundamental contact with the universe. It is interesting to ponder how humans would conceive of the universe if we had nothing more in the way of imaging apparatus at our disposal, as was the case for astronomers before Galileo. In contrast to the complex cosmologies currently pondered in modern physics, most of which involve an expanding universe shadowed by the afterglow of the Big Bang, the "first contact" provided by our eyes produces a model of the universe that is entirely limited to the Sun, Moon, and planets, the nearby stars, and the faint glow of the collective background of stars in our own Milky Way galaxy and a handful of other, nearby galaxies. From this simple thought experiment, it is clear that the bulk of the visible radiation arriving at Earth is emitted by stars.

But the apparent predominance of visible light from the Sun and nearby stars is in fact merely an accident of our particular position in the universe, combined with the evolutionary adaptation that gave our eyes maximal sensitivity at wavelengths of electromagnetic radiation that are near the maximum of the Sun's energy output. The Sun provides by far the majority of the visible radiation arriving at Earth strictly by virtue of its proximity. The brightest star in the night sky, Sirius (in the constellation Canis Major), actually has an intrinsic luminosity about 50 times larger than that of the Sun, but is about 8.6 light years distant (a light year is the distance traveled by light in one year, 9 × 10^{15} km; the Sun is about 8 light minutes from Earth). In turn, Sirius is only about one-hundred-thousandth as luminous as the star Rigel (in the neighboring constellation Orion),
but Sirius appears several times brighter than Rigel because it is about 50 times closer to us. Like the Sun, which has a surface temperature of about 6,000 K, most of the brightest stars have surfaces within the range of temperatures across which hot objects radiate very efficiently (if not predominantly) in the visible region. Representative stellar surface temperatures are 3,000 K for reddish Betelgeuse, a red supergiant in Orion; 10,000 K for Sirius; and 15,000 K for the blue supergiant Rigel (Fig. 1).

**Thermal Continuum Emission**

The tendency of objects at the temperatures of the Sun and stars to emit in the visible can be understood to first order via Planck’s Law, which describes the wavelength dependence of radiation emitted by a perfect blackbody. The peak of the Planck function lies within the visible regime for an object at a temperature of 6,000 K. This same fundamental physical principle tells us that objects much hotter or cooler than the Sun should radiate predominantly at wavelengths much shorter or longer than visible, respectively. Indeed, for a perfect blackbody, the peak wavelength of radiation is given by Wien’s displacement law (2),

\[ \lambda (\text{cm}) \sim \frac{0.51}{T (\text{K})} \]  

(1)

This relationship between the temperatures of objects and the wavelengths of their emergent radiation allows us to understand why Betelgeuse appears reddish and Rigel appears blue (Fig. 2).

**Figure 1.** The Hertzsprung–Russell diagram. The diagram shows the main sequence (Sun-like stars that are fusing hydrogen to helium in the cores), red giants, supergiants, and white dwarfs. In addition, the positions of the Sun, the twelve brightest stars visible from the Northern Hemisphere, and the white dwarf companions of Sirius and Procyon are indicated [Source: NASA (http://observe.ivv.nasa.gov/nasa/core.shtml.html)]. See color insert.

**Figure 2.** Wide-field photograph of Orion, illustrating the difference in color between the relatively cool star Betelgeuse (upper left) and the hot star Rigel (lower right). The large, red object at the lower center of the image, just below Orion’s belt, is the Orion Nebula (see Fig. 7). (Photo credit: Till Credner, AlltheSky.com) See color insert.

The same, simple relationship also provides powerful insight into astrophysical processes that occur across a very wide range of energy regimes (Fig. 3). The lowest energies and hence longest (radio) wavelengths reveal “cold” phenomena, such as emission from dust and gas in optically opaque clouds distributed throughout interstellar space in our galaxy. At the highest energies and hence shortest wavelengths (characteristic of X-rays and γ-rays), astronomers probe the “hottest” objects, such as the explosions of supermassive stars or the last vestiges of superheated material that is about to spiral into a black hole.

**Nonthermal Continuum Emission**

Certain radiative phenomena in astrophysics do not strongly depend on the precise temperature of the material and are instead sensitive probes of material density and/or chemical composition (3,4). For example, the emission from “jets” ejected from supermassive black holes at the centers of certain galaxies (Fig. 4) is said to be
“nonthermal” because its source is high-velocity electrons that orbit around magnetic field lines. Other, similar examples are the emission from filaments of ionized gas located near the center of our own galaxy and from the chaotic remnant of the explosion of a massive star in 1054 A.D. (the “Crab Nebula”). Such so-called “synchrotron radiation” often dominates radiation emitted in the radio wavelength regime (Fig. 5). Indeed, if human eyes were sensitive to radio rather than to visible wavelengths, the early mariners probably would have navigated by the Galactic Center and the Crab because they appear from Earth as the brightest stationary radio continuum sources in the northern sky. The synchrotron emission from the Crab is particularly noteworthy; it can be detected across a very broad wavelength range from radio through X ray (Fig. 6).

**Monochromatic (“Line”) Emission and Absorption**

**Deducing Chemical Compositions.** Astronomers use electronic transitions of atoms (as well as electronic, vibrational, and rotational transitions of molecules) as Rosetta stones to understand the chemical makeup of gas in a wide variety of astrophysical environments. Because each element or molecule radiates (and absorbs radiation) at a discrete and generally well-determined set of wavelengths—specified by that element’s particular subatomic structure—detection of an excess (or deficit) of emission at one of these specific wavelengths\(^1\) is both necessary and sufficient to determine the presence of that element or molecule. Hence, our knowledge of the origin and evolution of the elements that make up the universe is derived from astronomical spectroscopy (which might also be considered multiband, one-dimensional imaging).

Spectra obtained by disparate means across a very broad range of wavelengths can be used to ascertain both chemical compositions and physical conditions (i.e., temperatures and densities) of astronomical sources because the emissive characteristics of a given element depend on the physical conditions of the gas or dust in which it resides. For example, cold (100 K), largely neutral hydrogen gas emits strongly in the radio at 21 cm, whereas hot (10,000 K), largely ionized hydrogen gas emits at a series of optical wavelengths (known as the Balmer series). The former conditions are typical of the gas that permeates interstellar space in our own galaxy and in external galaxies, and the latter conditions are typical of gas in the proximity of very hot stars, which are sources of ionizing ultraviolet light. Such ionized gas also tends to glow brightly in the emission lines of heavier elements such as oxygen, nitrogen, sulfur, and iron (Fig. 7).

\(^1\) Such spectral features are called “lines,” because they appeared as dark lines in early spectra of the Sun.
Deducing Radial Velocities from Spectral Lines. Atomic and molecular emission lines also serve as probes of bulk motion. If a given source has a component of velocity along our line of sight, then its emission lines will be Doppler shifted away from the rest wavelength. The absorption or emission lines of sources that approach
and the subsequent nuclear fusion, in concentric shells, of converted to helium. The exhaust of core hydrogen and the subsequent nuclear fusion, in concentric shells, of hydrogen into helium and helium into carbon around the spent core causes the atmosphere of the star to expand, forming a red giant. Although the extended atmospheres of red giants are “cool” enough (∼3,000 K) for dust grains to condense out of the stellar gas, red giant luminosities can be huge (more than 10,000 times that of the Sun). This radiant energy pushes dust away from the outer atmosphere of the star at speeds of 10–20 km s⁻¹. The outflowing dust then collides with and accelerates the gas away from the star, as well. Eventually enough of the atmosphere is removed so that the hot, inert stellar core is revealed. This hot core is destined to become a fossil remnant of the original star: a white dwarf.

But before the ejected atmosphere departs the scene entirely, it is ionized by the intense ultraviolet light from the emerging white dwarf, which has cooled from core nuclear fusion temperatures (10⁷ to 10⁸ K) to a “mere” 10⁵ K or so. The ionizing radiation from the white dwarf causes the ejected gas to fluoresce, thereby producing a planetary nebula.

Because the varied conditions that characterize the evolution of planetary nebulae result in a wide variety of phenomena in any given nebula, such objects demand a multiwavelength approach to imaging. A case in point is the young planetary nebula BD +30° 3639 (Fig. 10). This planetary nebula emits strongly at wavelengths ranging from radio through X ray. The Chandra X-ray image shows a region of X-ray emission that seems to fit perfectly inside the shell of ionized and molecular gas seen in Hubble Space Telescope images and in other high-resolution images obtained from the ground. The optical and X-ray emitting regions of BD +30° 3639, which lies about 5,000 light years away, are roughly 1 million times the volume of our solar system. The X-ray emission apparently originates in thin gas that is heated by collisions between the “new” wind blown by the white dwarf, which is seen at the center of the optical and infrared images, and the “old,” photoionized red giant wind, which appears as a shell of ∼10,000 K gas surrounding the “hot bubble” of X-ray emission.

**REQUIREMENTS AND LIMITATIONS**

To understand the requirements placed on spatial resolution and sensitivity in astronomical imaging, we must consider the angular sizes and energy fluxes of astronomical objects and phenomena of interest. In turn, there are three fundamental sources of limitation on the resolution and limiting sensitivity (and hence quality) of astronomical images: the atmosphere, the telescope, and the detector.

**Spatial Resolution**

**Requirements:** Angular Size Scales of Astronomical Sources. Figure 11 shows schematically typical scales of physical size and distance from Earth for representative objects and phenomena studied by astronomers. Most of the objects of intrinsically small size, like the Sun, Moon, and the planets in our solar system, lie at small distances; we can study these small objects in detail only because they are relatively close, such that their angular sizes are substantial.
Within our own Milky Way galaxy, we observe objects that span a great range of angular size scales. The angular size of a Sun-like star at even a modest distance makes such stars a challenge to resolve spatially, even with the best available techniques. On the other hand, many structures of interest in our own Milky Way galaxy, such as star-forming molecular clouds and the expelled remnants of dying or expired stars, are sufficiently large that their angular sizes are quite large. Certain giant molecular clouds, planetary nebulae, and supernova remnants subtend solid angles similar to that of the Moon.

Just as for stars, the angular sizes of external galaxies span a very wide range. The Magellanic Clouds, which are the nearest members of the Local Group of galaxies (of which the Milky Way is the most massive and luminous member), are detectable and resolvable by the naked eye, whereas the Andromeda galaxy (a Local Group member that is a near-twin to the Milky Way) is detectable and resolvable with the aid of binoculars. The angular sizes of intrinsically similar galaxies in more distant galaxy clusters span a range similar to that of the planets in our solar system. The luminous cores of certain distant galaxies (“quasars”)—which can outshine their host galaxies—likely have sizes only on the order of that of our solar system; yet these are some of the most distant objects known, and hence quasars are exceedingly small in angular size. Galaxy clusters themselves are of relatively large angular size, simply by virtue of their enormous size scales; indeed, such clusters (and larger scale structures that consist of clusters of such clusters) probably represent the largest gravitationally bound structures in the universe. At still larger size scales lies the cosmic background radiation, the radiative remnant of the Big Bang itself. This radiation encompasses $4\pi$ steradians and has only very subtle variations in intensity with position across the sky.

3 The ejected envelopes of certain dying, sun-like stars were long ago dubbed “planetary nebulae” because their angular sizes and round shapes resembled the planets Jupiter and Saturn.
Of course, even within our solar system, there are sources of great interest (e.g., the primordial, comet-like bodies of the Kuiper Belt) that are sufficiently small that they are unresolvable by present imaging techniques. Sources of large angular sizes (such as molecular clouds, planetary nebulae, supernova remnants, and galaxy clusters) typically show a great wealth of structural detail when imaged at high spatial resolution. Thus, our knowledge of objects at all size and distance scales improves with any increase in spatial resolving power at a given wavelength.

Limitations

**Atmosphere.** Time- and position-dependent refraction by turbulent cells in the atmosphere causes astronomical point sources, such as stars, to "scintillate"; i.e., stars twinkle. Scintillation occurs when previously plane-parallel wave fronts from very distant sources encounter atmospheric cells and become distorted. Astronomers use the term "seeing" to characterize such atmospheric image distortion; the "seeing disk" represents the diameter of an unresolved (point) source that has been smeared by atmospheric distortion. Seeing varies widely from site to site, but optical seeing disks at visual wavelengths are typically not smaller than (that is, the seeing is not better than) \( \sim 1'' \) at most mountaintop observatories.

**Telescope.** The diameter of a telescope places a fundamental limitation on the angular resolution at a given wavelength. Specifically, the limiting angular resolution (in radians) is given by

\[
\theta \approx \frac{1.2 \lambda}{d}
\]

where \( \theta \) is the angle subtended by a resolution element, \( \lambda \) is the wavelength of interest, and \( d \) is the telescope diameter. This relationship follows from consideration of simple interference effects of wave fronts incident on a circular aperture, in direct analogy to plane-parallel waves of wavelength \( \lambda \) incident on a single slit of size \( d \). The resulting intensity distribution for a point source (known as the "point-spread function") is in fact a classical diffraction pattern, a central disk (the "Airy disk") surrounded by alternating bright and dark annuli. In ground-based optical astronomy using large telescopes, atmospheric scintillation usually dominates over telescope diffraction (that is, the "seeing disk" is much larger than the "Airy disk"), and such a diffraction pattern is not observed. However, in space-based optical astronomy or in ground-based infrared and radio astronomy, diffraction represents the fundamental limitation on spatial resolution.

**Detector.** Charge-coupled devices (CCDs) have been actively used in optical astronomy for more than two decades. During this period, CCD pixel sizes have steadily decreased, and array formats have steadily grown. As a result, CCDs have remained small and still maintain good spatial coverage. Detector array development at other wavelength regimes lags behind the optical, to various degrees, in number and spacing of pixels. However, almost all regimes, from X ray to radio, now employ some form of detector array. Sizes range from the suite of ten \( 1,024 \times 1,024 \) X-ray-sensitive CCDs aboard the orbiting Chandra X-Ray Observatory to the 37- and 91-element bolometer arrays used for submillimeter-wave imaging by the James Clerk Maxwell Telescope on Mauna Kea. These devices have a common goal of achieving a balance between optimal (Nyquist) sampling of the point-spread function and maximal image (field) size.

**Sensitivity**

**Requirements: Energy Fluxes of Astronomical Sources.** Astronomical sources span an enormous range of intrinsic luminosity. Figure 12 readily shows that the least luminous objects known tend to be close to Earth (e.g.,...
Figure 11. Physical radii vs. distances (from Earth) for representative astronomical sources (7). One astronomical unit (AU) is the Earth–Sun distance ($1.5 \times 10^8$ km). A light year is the distance traveled by light in one year ($9 \times 10^{12}$ km). Represented in the figure are objects within our own solar system, the nearby Sun-like star $\alpha$ Cen, the red supergiant Betelgeuse, the pulsar at the center of the Crab Nebula supernova remnant, a typical circumstellar debris disk ("CS_disk"), a typical planetary nebula (the Ring Nebula), the supernova remnant Cas A, the galactic giant molecular cloud located in the direction of the constellation Cygnus ("Cygnus_GMC"), the nearby Andromeda galaxy (M31), the quasar 3C 273, and the Virgo cluster of galaxies. Diagonal lines represent lines of constant angular size, and angular size decreases from upper left to lower right.

small asteroids in the inner solar system), and the most luminous sources known (e.g., the central engines of active galaxies or the primordial cosmic background radiation) are also the most distant. This tendency to detect intrinsically more luminous sources at greater distances follows directly from the expression for energy flux received at Earth,

$$ F = \frac{L}{4\pi D^2}, \quad (3) $$

where $F$ is the flux, $L$ is luminosity, and $D$ is distance. Thus an astronomical imaging system that has a limiting sensitivity $F \geq F_1$ penetrates to a limiting distance,

$$ D_l \leq \sqrt[3]{\frac{L}{4\pi F_1}}, \quad (4) $$

for sources of uniform luminosity $L$. Real samples (of, e.g., stars or galaxies), of course, may include a wide range of intrinsic luminosities. As a result, there tends to be strong selection bias in astronomy, such that the number and/or significance of intrinsically faint objects tends to be underestimated in any sample of sources selected on the basis of minimum flux.

For this reason in particular, astronomers require increasingly sensitive imaging systems. To calibrate detected fluxes properly, such systems must still retain good dynamic range, so that the intensities of faint sources can be accurately referenced to the intensities of bright, well-calibrated sources. In addition, because a given source of extended emission may display a wide variation in surface brightness, a combination of high sensitivity and good dynamic range frequently is required to characterize
source morphology adequately and, hence, deduce intrinsic source structure.

Limitations

Atmosphere. The Earth's atmosphere attenuates the signals of most astronomical sources. Signal attenuation is a function of both the path length through the atmosphere between the source and telescope and the atmosphere's intrinsic opacity at the wavelength of interest. Atmospheric attenuation tends to be smallest at optical and longer radio wavelengths, at which the atmosphere is essentially transparent. Attenuation is largest at very short (γ ray, X ray and UV) wavelengths, where the atmosphere is essentially opaque; attenuation is also large in the infrared. In the infrared regime especially, atmospheric transparency depends strongly on wavelength because the main source of opacity is absorption by molecules (in particular, water vapor).

The atmosphere also is a source of "background" radiation at most wavelengths, particularly in the thermal infrared and far-infrared (2 μm ≤ λ ≤ 1 mm), at which most of the blackbody radiation of the atmosphere emerges. This background radiation tends to limit the signal-to-noise ratio of infrared observations for which other noise sources (such as detector noise) are minimal. Elimination of thermal radiation from the atmosphere provides a primary motivation for the forthcoming Space Infrared Telescope Facility (SIRTF), the last in NASA's line of Great Observatories.

Telescope. Sensitivity (or image signal-to-noise ratio) is directly proportional to the collecting area and efficiency of the telescope optical surfaces ("efficiency" here refers to the fraction of photons incident on the telescope optical surface that are transmitted to the camera or detector). Reflecting telescopes supplanted refracting telescopes at the beginning of the twentieth century because large primary mirrors could be supported more easily than large

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Figure 12. Intrinsic luminosities vs. distances (from Earth) for representative astronomical sources; symbols are the same as in the previous figure. Luminosities are expressed in solar units, where the solar luminosity is 4 × 10^{33} \text{ erg s}^{-1}. Diagonal lines represent lines of constant apparent brightness, and apparent brightness decreases from upper left to lower right.
objective lenses and the aluminized surface of a mirror provides nearly 100% efficiency at optical wavelengths. Furthermore, unlike lenses, paraboloids provide images that are free of spherical or chromatic aberrations. These same mirrors provide excellent efficiency and image quality in the near-infrared, as well. Parabolic reflectors are also used as the primary radiation collecting surfaces in the radio regime, where the requirements of mirror figure are less stringent (due to the relatively large wavelengths of interest).

**Detector.** The photon counting efficiency of a detector and sources of noise within the detector also dictate the image signal-to-noise ratio. Photon counting efficiency is usually referred to as detector quantum efficiency (QE). Detector QEs at or higher than 80% are now feasible in many wavelength regimes; however, such high QE often comes at the price of the introduction of noise. Typical image noise sources are read noise, the inherent uncertainty in the signal readout of the detector, and dark signal, the signal registered by the detector in the absence of exposure to photons from an external source.

**Surmounting the Obstacles**

Beating the Limitations of the Atmosphere: Adaptive Optics and Space-Based Imaging. Adaptive optics techniques have been developed to mitigate the effects of atmospheric scintillation. In such systems, the image of a fiducial point source—a bright star or a laser-generated artificial “star”—is continuously monitored, and these data are used to drive a quasi-real-time image correction system (typically a deformable or steerable mirror). Naturally—as has been demonstrated by the spectacular success of the refurbished Hubble Space Telescope—placement of the telescope above the Earth’s atmosphere provides the most robust remedy for the effects of atmospheric image distortion.

Beating the Limitations of Aperture: Interferometry. The diffraction limit of a single telescope can be surmounted by using two or more telescopes in tandem. This technique is referred to as “interferometry” because it uses the interference patterns produced by combination of light waves from multiple sources. Therefore, the angular resolution of such a multiple telescope system, at least in one dimension, is limited by the longest separation between telescopes, rather than by the aperture of a single telescope. However, it is generally not possible to “fill in” the gaps between two telescopes at large separation by using many telescopes at smaller separation. As a result, interferometry is generally limited to relatively bright sources, and interferometric image reconstruction techniques necessarily sacrifice information at low spatial frequencies (i.e., large-scale structure) in favor of recovering information at high spatial frequency (fine spatial structure). Interferometry has long been employed at radio wavelengths because recombination of signals from multiple apertures is relatively easy at long wavelengths. Indeed, the angular resolution achieved routinely at centimeter wavelengths by NRAO’s Very Large Array in New Mexico rivals or exceeds that of optical imaging by the Hubble Space Telescope. Recently, however, several optical and infrared interferometers have been developed and successfully deployed; examples include the Navy Prototype Optical Interferometer at Anderson Mesa and the Infrared Optical Telescope Array on Mt. Hopkins, both in Arizona, and the optical interferometer operated at Mt. Wilson, California, by the Center for High Angular Resolution Astronomy.

Beating the Limitations of Materials: Mirror Fabrication. The sheer weight of monolithic, precision-ground mirrors and the difficulty of maintaining the requisite precise figures renders them impractical for constructing telescope apertures larger than about 8 meters in diameter. Hence, during the late 1980s and early 1990s, two competing large mirror fabrication technologies emerged: spin-cast and segmented mirrors (Fig. 13). Both methods have yielded large mirrors whose apertures are far lighter and more flexible than previously feasible. The former method has yielded the 8-meter-class mirrors for facilities such as the twin Gemini telescopes, and the latter method has yielded the largest mirrors thus far, for the twin 10-meter Keck telescopes on Mauna Kea. It is not clear, however, that either technique can yield optical-quality mirrors larger than about 15 meters in diameter.

An entirely different mirror fabrication approach is required at high energies because, for example, X rays are readily absorbed (rather than reflected) by aluminized glass mirrors when such mirrors are used at near-normal incidence. The collection and focusing of X-ray photons instead requires grazing incidence geometry to optimize efficiency and nested mirrors to optimize collecting surface (Fig. 14). The challenge now faced by high-energy astronomers is to continue to increase the effective area of such optical systems while meeting the strict weight requirements imposed by space-based observing platforms. It is not clear that facilities larger than the present Chandra and XMM-Newton observatories are practical given present fabrication technologies; indeed, Chandra was the heaviest payload ever launched aboard a NASA Space Shuttle.

**THE SHAPE OF THINGS TO COME**

Projects in Progress

At this time, several major new astronomical facilities are partially or fully funded and are either in design or under construction. All are expected to accelerate further the steady progress in our understanding of the universe. A comprehensive list is beyond the scope of this article; however, we mention a few facilities of note.

- The Space Infrared Telescope Facility (SIRTF): SIRTF is a modest-aperture (0.8 m) telescope equipped with instruments of extraordinary sensitivity for observations in the 3 to 170 µm wavelength regime. SIRTF features a powerful combination of sensitive, wide-field imaging and spectroscopy at low to moderate resolution over this wavelength range. It is well equipped to study (among many other things) primordial galaxies, newborn
stars and planets, and dying stars because all of these phenomena emit strongly in the mid- to far-infrared. SIRTF has a projected 5-year lifetime and is expected to be deployed into its Earth-trailing orbit in 2002.

- The Stratospheric Observatory for Infrared Astronomy (SOFIA): SOFIA will consist of a 2.5-meter telescope and associated cameras and spectrometers installed aboard a Boeing 747 aircraft. SOFIA will be the largest airborne telescope in the world. Due to its ability to surmount most of Earth’s atmosphere, SOFIA will make infrared observations that are impossible for even the largest and highest ground-based telescopes. The observatory is being developed and operated for NASA by a consortium led by the Universities Space Research Association (USRA). SOFIA will be based at NASA’s Ames Research Center at Moffett Federal Airfield near Mountain View, California. It is expected to begin flying in the year

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**Figure 13.** Photo of the segmented primary mirror of the 10-meter Keck telescope (Photo credit: Andrew Perala and W.M. Keck Observatory). See color insert.

**Figure 14.** Geometry of the nested mirrors aboard the orbiting Chandra X-Ray Observatory [Source: NASA/Chandra X-Ray Center (http://chandra.harvard.edu)]. See color insert.
2004 and will remain operational for two decades. Like SIRTF, SOFIA is part of NASA’s Origins Program, and hence its science goals are similar and complementary to those of SIRTF.

- The Atacama Large Millimeter Array (ALMA): ALMA will be a large array of radio telescopes optimized for observations in the millimeter-wavelength regime and situated high in the Atacama desert in the Chilean Andes. Using a collecting area of up to 10,000 square meters, ALMA will feature roughly 10 times the collecting area of today’s largest millimeter-wave telescope arrays. Its telescope-to-telescope baselines will extend to 10 km, providing angular resolution equivalent to that of a diffraction-limited optical telescope whose diameter is 4 meters. ALMA observations will focus on emission from molecules and dust from very compact sources, such as galaxies at very high redshift and solar systems in formation.

Recommendations of the Year 2000 Decadal Review

The National Research Council, the principal operating arm of the National Academy of Sciences and the National Academy of Engineering, has mapped out priorities for investments in astronomical research during the next decade (8). The NRC study should not be used as the sole (or perhaps even primary) means to assess future directions in astronomy, but this study, which was funded by NASA, the National Science Foundation, and the Keck Foundation, does offer insight into some potential ground-breaking developments in multiwavelength astronomical imaging.

Highest priority in the NRC study was given to the Next Generation Space Telescope (NGST). This 8-meter-class, infrared-optimized telescope will represent a major improvement on the Hubble Space Telescope in both sensitivity and spatial resolution and will extend space-based infrared imaging into the largely untapped 2–5 µm wavelength regime. This regime is optimal for studying the earliest stages of star and galaxy formation. NGST presently is scheduled for launch in 2007.

Several other major initiatives were also deemed crucial to progress in astronomy by the NRC report. Development of the ground-based Giant Segmented Mirror Telescope was given particularly high priority. This instrument has as its primary scientific goal the study of the evolution of galaxies and the intergalactic medium. Other projects singled out by the NRC report include

- Constellation-X Observatory, a next-generation X-ray telescope designed to study the origin and properties of black holes;
- a major expansion of the Very Large Array radio telescope in New Mexico, designed to improve on its already unique contributions to the study of distant galaxies and the disk-shaped regions around stars where planets form;
- a large ground-based survey telescope, designed to perform repeated imaging of wide fields to search for both variable sources and faint solar-system objects (including near-Earth asteroids and some of the most distant, undiscovered objects in the solar system); and
- the Terrestrial Planet Finder, a NASA mission designed to discover and study Earth-like planets around other stars.

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IMAGING SCIENCE IN BIOCHEMISTRY

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INTRODUCTION

Research in biology, aimed at understanding the fundamental processes of life, is both an experimental and an observational science. During the last century, all classes of biomolecules relevant to life have been discovered and defined. Consequently, biology progressed from cataloging species and their life styles to analyzing their underlying molecular mechanisms. Among the molecules required by life, proteins represent certainly the most fascinating class because they are the actual “working molecules” involved in both the processes of life and the structure of living beings. Proteins carry out diverse functions, including signaling and chemical communication (for example kinases and hormones), structure (keratin and collagen), transport of metabolites (hemoglobin), and transformation of metabolites (enzymes).

In contrast to modeling and simulation, observation and analysis are the main approaches used in biology. Early biology dealt only with the observation of macroscopic phenomena, which could be seen by the naked eye. The development of microscopes permitted observation of the smaller members of the living kingdom and hence of the cells and the organelles they contain (Fig. 1). Observing