Astronomers must move observatories into space

Jim Everett reviews the technological frontiers facing astronomy and astrophysics, from 1,000-meter radiowaves to the finest gamma rays.

Lyndon LaRouche's proposal to establish a large scientific colony on Mars during the 2020s and 2030s conjures up the prospect of large-scale astrophysical undertakings—such as his suggestion of a "lens with an aperture on the scale of the Mars orbit." (*Fusion,* November-December 1986.) While space scientists and astrophysicists have tended to trim their imaginations to fit their threadbare budgets, the frontiers they are facing even today point the way to more majestic undertakings. Earth's atmosphere is the principal frontier that is now being conquered.

The Earth's atmosphere, precisely because it is protective of life, is a hindrance to understanding the universe that lies beyond. The ozone layer shields ultraviolet radiation from both the delicate chemistry of living organisms and the astronomer's probing telescope.

Our increasing ability to move both man and machine above the atmosphere is the first sure step toward ushering in the golden age of astronomy. Probably the greatest part of astronomy—in terms of man-hours—will continue to be practiced from the surface of Earth for some time to come. The advent of computerized detection devices and innovative arrays of mirrors has lengthened and sharpened the view of ground-based telescopes enormously. But, from the ground, we are near our theoretical limits in visible light; in both the high and low-energy portions of the spectrum, the sky is a nearly opaque screen (see **Figure 1**).

In the solar system, the advantages of observing from space are obvious. The Vikings and the Voyagers have increased our planetary knowledge far more than it had advanced in the previous two millennia. Simply being able to see the planets and their moons clearly and at close range has revolutionized planetary astronomy. This ability to place telescopes in orbit is revolutionizing all branches of astronomy. Of all the sciences, astronomy is least able to perform experiments on its subject, relying instead on technological improvements in observation to furnish fresh constraints and problems for theory.

Consider infrared astronomy: This part of the electromagnetic spectrum is responsible for our sensation of heat. All objects about us, including the air and even the telescopes themselves, emit radiation in these wavelengths. How do you look at the infrared emission of a star from the Earth? In visible light, this would be like looking at the stars in the daytime with a telescope that has been painted with phosphorescent paint! Using a few natural "windows" and some very advanced technology, infrared astronomers have to a significant degree overcome their blindness. Imagine, though, seeing in the infrared far above the warm Earth. The Infrared Satellite did this for 10 months in 1983, producing the first complete map of the sky in infrared radiation. Astronomers are still poring over these maps, making new discoveries.

The x-ray barrier was broken in 1978 with the launch of the Einstein X-Ray Observatory. For two-and-a-half years, it mapped the high-energy universe. Perhaps its most exciting discovery was the existence of a uniform x-ray background radiation, which apparently is generated beyond our galaxy. It is as if intergalactic space were illuminated by a 400-million-degree plasma. Einstein shut down when it ran out of the gas needed to keep it oriented in space. Two orbiting gamma-ray telescopes were also launched in the 1970s, the American SAS-2 and the European Space Agency's COS-B. These discovered some of the sources of gamma rays, the most energetic of photons.

All of these pioneer space telescopes are now shut down, some on schedule, some by malfunction. The last active solar system mission is Voyager 2. The Uranus encounter of last year and the hoped-for Neptune rendezvous in 1989 are scientific bonuses; the Voyager craft were designed only to work as far as Saturn. After 1989, the entire fleet of space explorers designed in the 1970s will be dead.

The design for the next generation of space-based telescopes is now complete. The Hubble Space Telescope, designed for optical light, is ready for launch now, awaiting the first available Space Shuttle sometime next year. The Gamma-Ray Observatory is also nearly ready for launch. Other missions still in the design stage include the Advanced X-Ray Astrophysics Facility, the Extreme Ultraviolet Explorer, the Space Infrared Telescope Facility, Quasat (for Quasar Satellite, a radio telescope), and several smaller instruments that will operate on Spacelab missions.

Except for the Space Telescope and the Gamma-Ray Observatory, none of these other missions have anything like a firm launch date, causing a wave of pessimism to ripple through the astrophysics community. As budgetary commitments become harder to obtain, a difficulty arises in attracting the best scientists to these projects. Even in the relatively productive 1960s and 1970s, the time from conception to launch of a major space probe was from 10 to 15 years. That time is now even longer. Many of the scientists involved in the earlier missions will no longer be active during the 1990s when many of the planned missions are very tentatively scheduled for launch. How can young scientists be attracted, in the peak of their creative years, to the full-time job of planning and organizing a venture that will not make any scientific returns for 15 or 20 years?

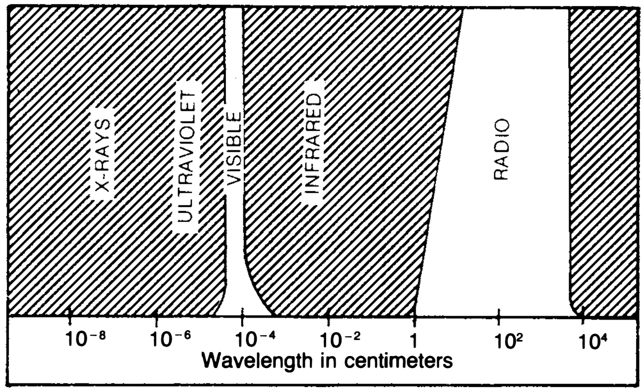
NASA has wisely balanced the parallel needs of pure science with our task of learning how to live and work in space. To astrophysicists, manned missions often seem an expensive way to accomplish what an unmanned mission could do better. They are increasingly expressing resentment at the proportion of the NASA budget going to the Shuttle, for instance. Given the relatively low cost of unmanned missions, especially with state-of-the-art technology, astrophysicists might be better advised to increase educational efforts directed at Congress and the public in general. Few in the general public realize why money should be spent to place telescopes in orbit. Overall funding must be increased, rather than have programs vital to national progress in competition over a shrinking pie. The two programs are, after all, complementary. The manned program will sustain automated space telescopes by enabling them to be repaired.

To deepen and intensify the debate over space-based telescopes, the problems of observing from Earth's surface in each part of the electromagnetic spectrum are summarized below. All electromagnetic radiation obeys the same laws of optics, although the extreme differences in wavelength, from 1,000 meters down to .00001 nanometers, require radically different modes of detection.

The two limiting factors in any particular detector are intensity detectability and time and spatial resolution. Intensity is optimized by increasing the surface area of the tele-

FIGURE 1

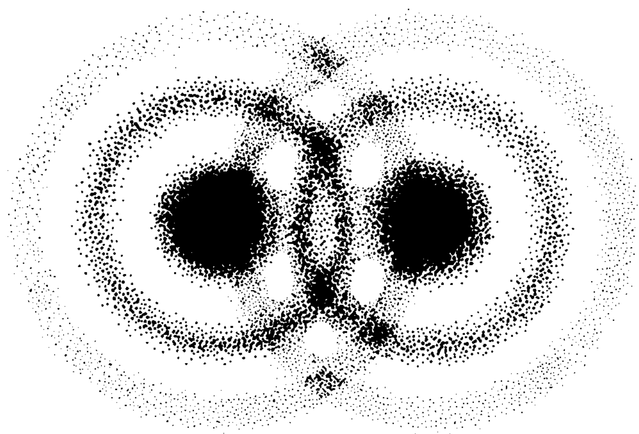
Visual capability of exo-atmospheric telescopes



The atmosphere is transparent only for radio and visible wavelengths. Even for these wavelengths, there are great advantages in moving the telescopes into space.

FIGURE 2

How two point sources appear through any aperture



Most of the light from each point source is contained in the small central area called the Airy disc, after George Airy who first solved the wave equations in 1835. This disc will be surrounded by concentric circles of interference patterns at a distances of (1.22 × λ)/d, (2.233 × λ)/d, (3.238 × λ)/d, . . . where λ is the wavelength of light being imaged, and d is the diameter of the aperture. Successive circles are less and less bright. Hence, if d is made increasingly large, the concentric circles become smaller, converging on the central point. An infinitely large aperture allows a point source to be imaged as a perfect point. Resolution is thus limited by the aperture of the telescope.

scope, which in principle has no fixed limit. Resolution is determined by the interaction of light with the aperture of a telescope. Light is diffracted when it passes through a lens or is reflected by a mirror, spreading spherically outward. The resolution of the resulting image will be limited by the interference patterns created by the multiple waves created in different parts of the aperture. The result is that resolution is limited by the size of a telescope's aperture, whether lens, mirror, or dish (see **Figure 2**). Although no limit exists in principle for the aperture size, with shorter wavelengths the technological barriers are severe, involving configuring a large surface to within about 1/100th of a wavelength. What are the current technological limitations to increasing intensity and resolution in each of the major segments of the electromagnetic spectrum?

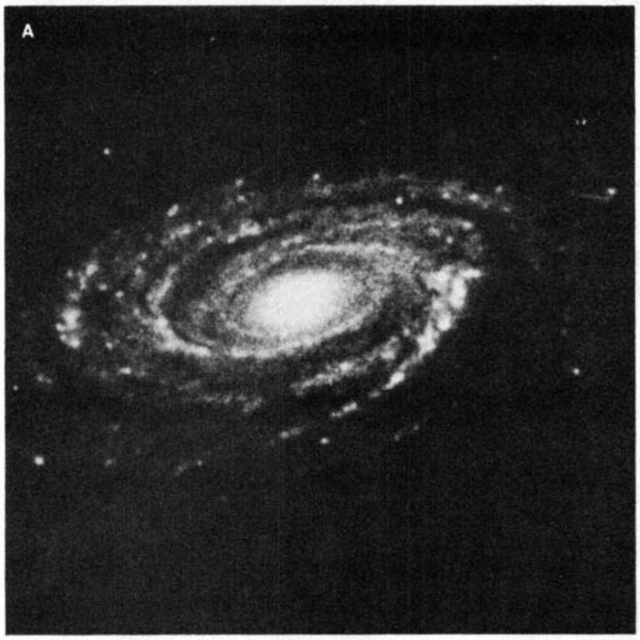
Radio—1,000 meters to 1 millimeter

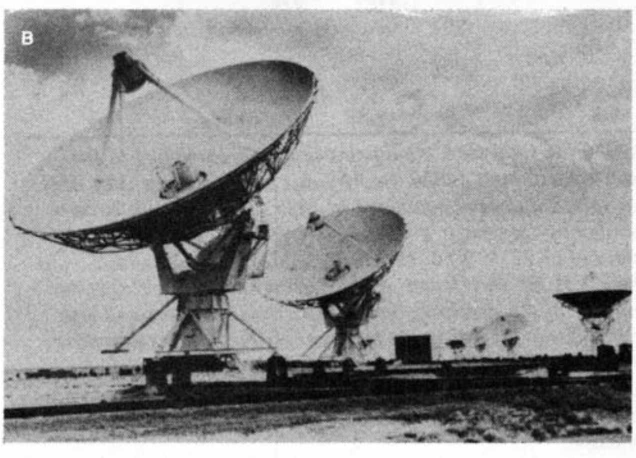
The radio portion of the spectrum is usually defined as extending from 1 millimeter to the far end of the spectrum, although the longest wavelengths are currently inaccessible because they are reflected back into space by the Earth's ionosphere. Except for possibly the shortest wavelengths, radio waves are usually of non-thermal origin, being generated either as synchrotron radiation in magnetic fields of stars or the galaxy as a whole, or the result of certain atomic and molecular transitions. These latter include the important radio emission of hydrogen gas at 21 centimeters wavelength that makes possible the identification of the spiral arms of our own galaxy (see **Figures 3 and 4**).

The progress of radio astronomy has been more closely linked to the development of the computer than other types

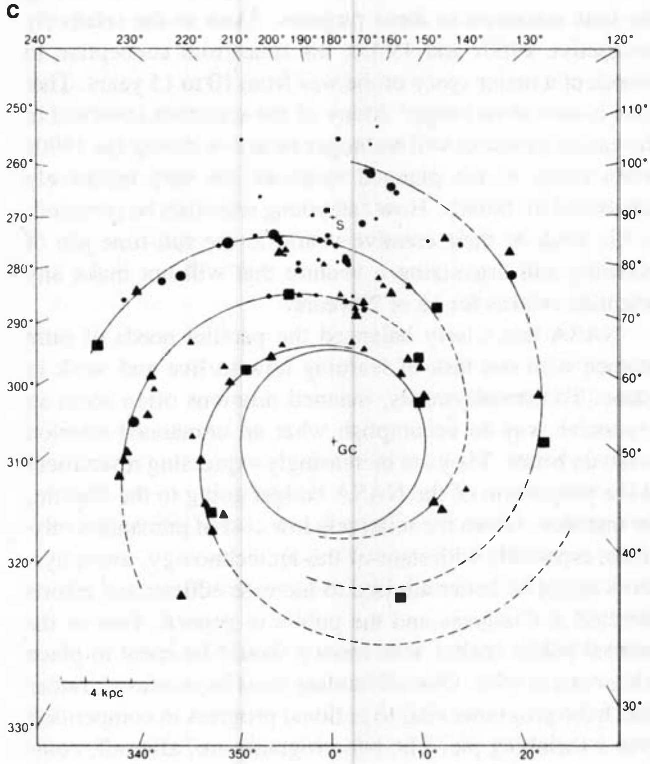
FIGURE 3

Mapping our spiral galaxy





(a) U.S. Naval Observatory; (b) Yvonne Georgelin; (c) NRAO



We live in a spiral galaxy somewhat like NGC 5985 shown in (a). Until radio telescopes mapped the hydrogen gas concentrations in our own galaxy (b), we had no way of detecting its spiral arms. GC = galactic center; S = Sun. Triangles and squares are hydrogen concentrations visible at radio wavelengths. Circles are those visible at optical wavelengths. Overall diameter is 100,000 light-years. Shown in (c) is the Very Large Array in the Plain of St. Augustine near Socorro, N.M., a radio telescope operated by the National Radio Astronomy Observatory. It arranges 27 identical dishes in a Y-shaped configuration. Each arm is about 12 miles long.

of astronomy. This is because of the difficulties in imaging very long wavelengths with high resolution. A comparison of the 200-*inch* Mt. Palomar optical telescope with the 300-*foot* radio dish at Green Bank, West Virginia, illustrates the point. In blue-green light, the optical telescope has a theoretical resolution of .025 arc seconds, while the radio telescope's resolution is only 5 arc minutes when observing at 10 cm. The human eye, with a resolution of 1-2 arc minutes, is much better than the 300-foot radio telescope. The early, postwar radio telescopes could only paint the radio sky with a very broad brush.

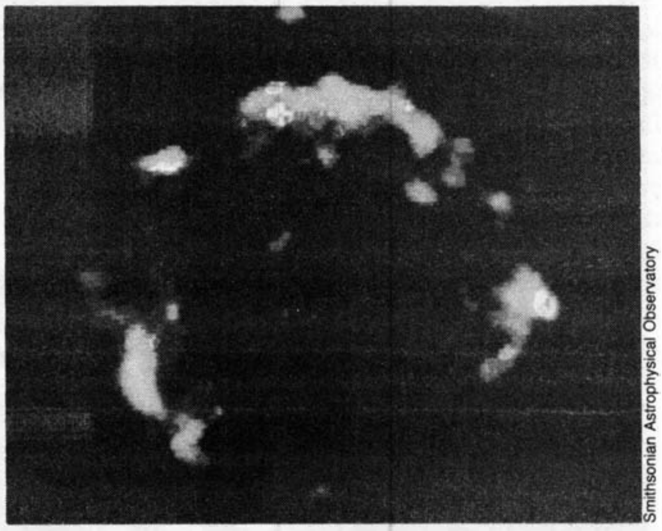
Since Michelson's interferometer experiments at the turn of the century, astronomers have known of the possibility of using two or more separate apertures to increase the effective aperture and therefore the resolution of a telescope. In the 1950s, the first radio telescope arrays were built. A number of technological problems limited the success of these efforts. First, the telescopes had to be directly linked so that the electric pulses generated by the radio waves could be brought together to form interference patterns. Second, the resulting interference patterns could get extremely difficult to interpret.

As computers became available, these problems began to diminish. By the 1960s a technique called very-long-baseline interferometry (VLBI) was used to link telescopes over 100 km apart, allowing for a resolution of .05 arc seconds. In 1967, the technique was perfected by digitizing the data at each telescope and storing it along with the "ticks" from atomic clocks, then combining it later with the help of a special computer called a correlator. The Canadians who first developed this approach achieved a resolution of .02 arc seconds observing 3C 273B, a distant quasar.

VLBI is limited because a few widely separated telescopes cannot "fill in" the entire synthetic aperture. Three radio dishes in a straight line will not produce a correct two-dimensional image. The Very Large Array (VLA), in New Mexico, successfully addresses this problem, producing radio maps with very little geometrical distortion and with a resolution of 0.13 arc seconds at 2 centimeters, which is 10 times better than any Earth-based optical telescope, operating with conventional imaging techniques. It does this by directly connecting a Y-shaped array of 27 radio telescopes, each with an aperture of 25 meters. The entire array has the performance of a single collector 27 km in diameter. The optics of the VLA are far in advance of its computing power. It is in urgent need of supercomputing capability, especially in the area of spectral analysis.

The next big step in radio astronomy will be the Very Long Baseline Array (VLBA), due to be completed in the mid-1990s, which will have ten 25-meter telescopes distributed from Hawaii to the Atlantic Coast. This system, especially when operated with a Canadian VLBA and with the VLA, will combine high resolution with a good "brightness" because of the density of the network. According to Mark Gordon of the National Radio Astronomy Observatory, it

FIGURE 4
Composite image of a supernova remnant



This image of a supernova remnant, a shell of expanding gas known as Cassiopeia A, is a composite of x-ray, visible light, and radio images. The shell is discernible thanks to the x-ray and radio contributions.

"will be able to make radio maps showing features only 200 *millionths* of an arc second across—the thickness of a nickel seen at a distance of 2,000 miles!"

NASA and ESA are in the early stages of planning a space-based radio observatory called Quasat, a single 10-15 m radio telescope in Earth orbit (see **Figure 5**). Quasat will be linked with the VLBA and VLA on Earth for interferometry—that is, two-dimensional imaging. Because Quasat will be placed in a precessing elliptical orbit, the satellite's path will constantly be shifting within the same plane, thus filling in the aperture and thereby increasing the field of view. The typical mode of operation will be to observe some source for a period of one orbit, then repeat the observation at a later time in the precession cycle, all the while integrating the results in a computer. Resolution is expected to be around 0.0001 arc seconds. Quasat will be able to work in the southern hemisphere also, where there is currently little radio observing capability.

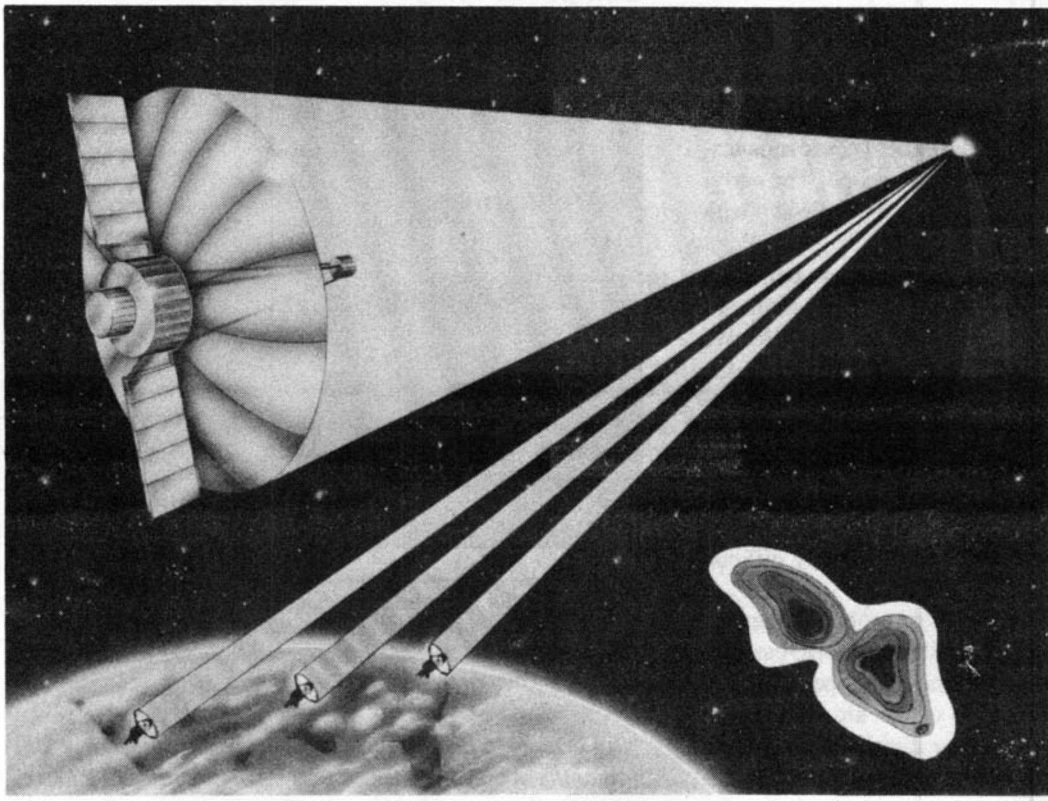
The Soviet Union has approved funding for Radio Astron, which will be similar in design to Quasat. The Soviets are actively seeking Western technological cooperation. Many Western scientists are eager to accept, since the projected launch will be years ahead of Quasat, which has not yet been approved for funding.

Infrared—1 millimeter to 700 nanometers

Infrared wavelengths are commonly measured in microns, 1/1,000th of a millimeter. Thus the infrared spectrum stretches from 1,000 microns (1 mm) down to 0.7 microns.

FIGURE 5

High-resolution radio interferometry from space



Artist's conception of Quasat, a radio telescope proposed by NASA and the European Space Agency to be based in Earth orbit and linked to ground-based radio telescopes. The image of a distant object (lower right) is made up of contours of equal intensity of radio emission.

The infrared spectrum is itself subdivided into five sections, based primarily on the different conditions for detection (see **Figure 6**).

Submillimeter—1,000 to 300 microns

The submillimeter band combines techniques from both infrared and radio astronomy. Submillimeter radiation is emitted by a number of molecules, such as carbon monoxide, hydrogen cyanide, and sulfur dioxide. One of the major tasks of submillimeter astronomy is to map the distribution of these molecules, since they are a valuable tracer to large neutral hydrogen clouds, which are themselves difficult to observe directly.

The same molecules that emitted submillimeter radiation deep in space are also present in the atmosphere, so the atmosphere is a strong absorber. A few windows do exist, however, that permit a certain percentage of the radiation to reach the surface. Placing telescopes high on mountain tops, above most atmospheric water vapor, greatly improves their performance. A number of 10- to 15-meter telescopes are under construction at the present time. The current leaders are the Franco-German IRAM team, who are building three 15-meter telescopes in an array near Grenoble, France.

The surfaces of submillimeter telescopes must be more precisely configured than in radio astronomy. To achieve a sharp focus the surface should be around 1/20th of a wavelength (0.01 mm). Like all infrared telescopes, the next great leap in performance will be with space-based instruments, primarily to get above the absorption layers of the atmosphere.

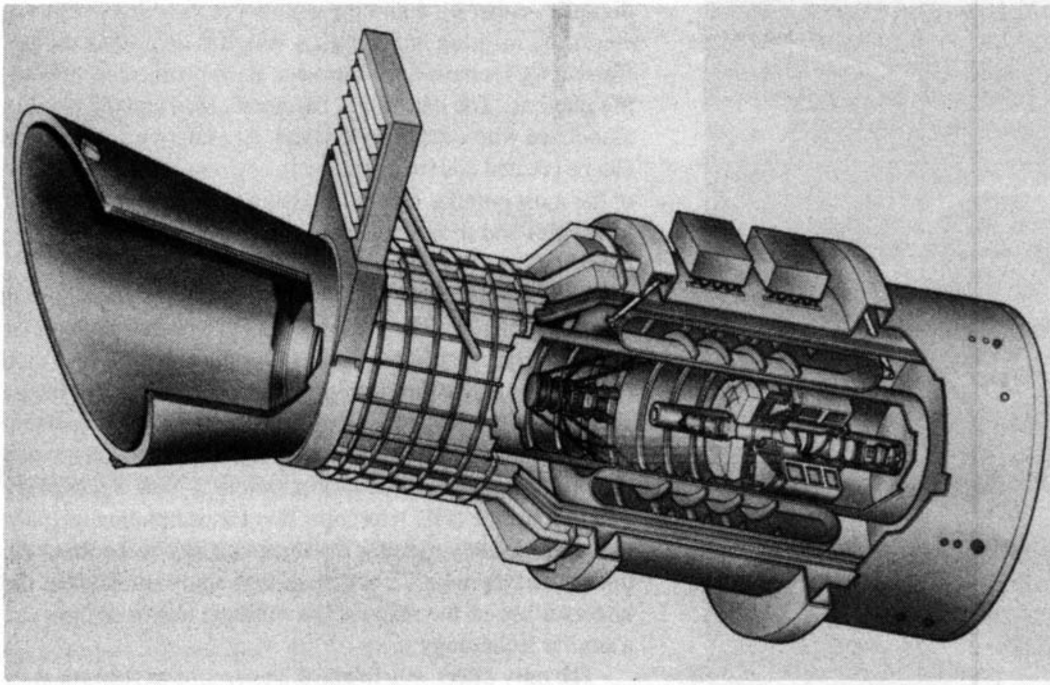
Far infrared—300 to 40 microns

Far infrared radiation is very strongly absorbed by the atmosphere; there are no windows at all in this region. In past years the only observations were with balloon-borne instruments and with the Kuiper Airborne Observatory, a NASA operated 0.9 m telescope flown in a C141 transport. This wavelength opened up dramatically in 1983 with the launch of the IRAS satellite. Until the launching of IRAS, the catalogue of far infrared objects contained just 2,000 items. It now has a third of a million. The 0.6 m telescope was shielded from solar heating by 70 kg of liquid helium, which kept the instrument at 16 K and the solid state detector at 2 K. The low temperatures were required to keep the instrument itself from emitting the radiation it was supposed to be gathering.

Middle infrared—40 to 4 microns

There are several atmospheric windows in the middle infrared, but since matter at 273 K (0° C) emits thermal radiation in this wavelength range, the sky and even the

FIGURE 6
Infrared telescope assembly for SIRTF



Engineer's depiction of the infrared telescope assembly, the major part of the Shuttle Infrared Telescope Facility (SIRTF). The telescope and detection instruments will be cooled to near absolute-zero by superfluid helium.

are strong sources of middle infrared.

Computer technology provides a method of subtracting out this background noise. Called "nodding," the telescope quickly shifts back and forth between the point source of light being observed and an empty patch of sky. The computer then subtracts the radiation detected in the "empty" frame from the star frame. New advances now permit extended images to be photographed directly, using CCD imaging with a bismuth-doped silicon chip with 1,024 pixels.

Near infrared—4 to 1.1 microns

Near infrared is not scattered by the atmosphere and there are a number of observing windows. Since it is not scattered, even daytime observation is possible and some of the largest optical telescopes are routinely used in the daytime "off hours" for near infrared work. The biggest technological challenge is detection of the radiation. Currently the best detectors are made of indium antimonide, which varies in electrical conductivity when struck by near infrared, much as a light meter does with visible light. This detector must be chilled to 50° K. The brightest objects in the near infrared are the late-type giants, such as Betelgeuse and Antares.

Photographic infrared—1.1 to 0.7 microns

This is the shortest infrared wavelength and it behaves in every way like visible light. The human eye does not respond to this wavelength, but photographic emulsions are receptive. Charge-coupled device detectors are extremely efficient in the photographic infrared.

Visible light—700 to 300 nm

The atmosphere is transparent to visible light, but visible light telescopes on Earth still cannot reach the theoretical limits of resolution and light capture. The 200-inch Palomar telescope has a theoretical resolution of 0.02 arc seconds, but in practice the very best attainable resolution is only 0.2 arc seconds and for long exposures not better than 1.0 arc seconds. By comparison, the theoretical resolution of a 6-inch amateur telescope is 1.0 arc seconds. The degradation in resolution is caused by atmospheric turbulence. This turbulence is worse in the lower atmosphere, so the newest telescopes are being constructed on remote mountain tops, such as Mauna Kea in Hawaii.

Light capture has increased almost two orders of magnitude in the last decade, due to advances in detector technology. At the time the 200-inch was built, photographic emulsion had an efficiency of 1/300, capturing 1 photon of every

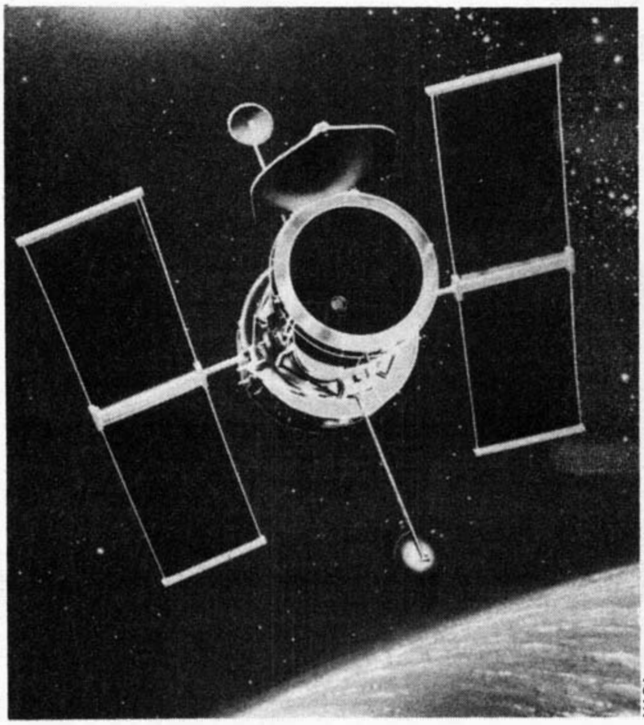
GLOSSARY

Arc second. Angular measure of the heavens. Sixty seconds of arc make one arc minute. Sixty arc minutes make one degree of angular measure.

Nanometer. One-billionth of a meter.

CCD. Charge-coupled device. An electronic device used instead of photographic film. The number of photons striking each square ("pixel") of a very fine grid is recorded. Used for very faint light sources.

FIGURE 7



Peering 'far out into space and far back in time'
Scheduled for launch on the Shuttle in 1988, the Hubble Space Telescope will be able to see stars and galaxies 50 times dimmer than those visible from Earth, with only a 2.4-meter mirror.

300. That has now been improved to 1/30. By contrast, CCD detectors have an efficiency of 3/4. A 13-inch amateur reflector, if coupled to a CCD, would have greater effective light-gathering power than the 200-inch when it was used with the old photographic emulsions!

Now that nearly all the light-gathering power of modern telescopes is being utilized, the push is on for larger aperture instruments, using multiple mirrors or adaptive optics (see below) or both. The University of Texas is planning a 7.6 m (300-inch) reflector and the University of California is working on a 10-meter reflector made up of 36 smaller hexagonal segments. Another approach is to make a number of separate telescopes share the same focus. The Multiple Mirror Telescope at Mt. Hopkins, Arizona uses this principle. Its six 1.8 m mirrors give an effective aperture of 4.5 m, which makes it the world's third-largest telescope. The designers of the Multiple Mirror are working on a larger version, the National New Technology Telescope, one with eight mirrors of 5 m, creating in effect a 14 m telescope.

While there is no theoretical limit to light-gathering power, the problem of increased resolution is more difficult. For Earth-based telescopes the answer is to use a combination of computer processing of images created by CCDs or some other electronic detector, and adaptive optics. Computer processing is now being used extensively. Images are stored digitally, either by digitizing a photograph with a densitometer or by imaging with a CCD, which is inherently digital. Current CCDs have 64,000 pixels. Each pixel counts incoming photons. The detector is frequently read and the number associated with each pixel is saved. At a later time, the image can be created and manipulated in any number of ways. One of the most popular ways is to assign false colors to different intensities and then display the color image on a color video monitor.

The adaptive optics approach to increased resolution is still in its infancy. The basic idea is to continuously monitor the variations in direction of incoming radiation and then either physically adjust the optical surfaces to keep the image close to the theoretical limit and/or use computer processing to correct for distortions. The physical approach will be used on the European Southern Observatory's New Technology Telescope. The NTT telescope, due for completion in 1988, will continuously monitor the image quality and correct the mirror surface with 75 actuators that apply pressure to the undersurface of the mirror. The multiple mirror designs use a similar technology.

The only direct way to allow a telescope to perform at its theoretical limits of resolution is to move it into space. The 2.4 m Hubble Space Telescope (HST) will have a resolution of 0.06 arc seconds, more than an order of magnitude better than any ground-based telescope. While only the 15th largest telescope, it will nonetheless be able to see dimmer objects than any other, because its images will not be fogged by airglow. The HST will be able to see stars and galaxies 50 times dimmer than those visible from Earth (see **Figure 7**).

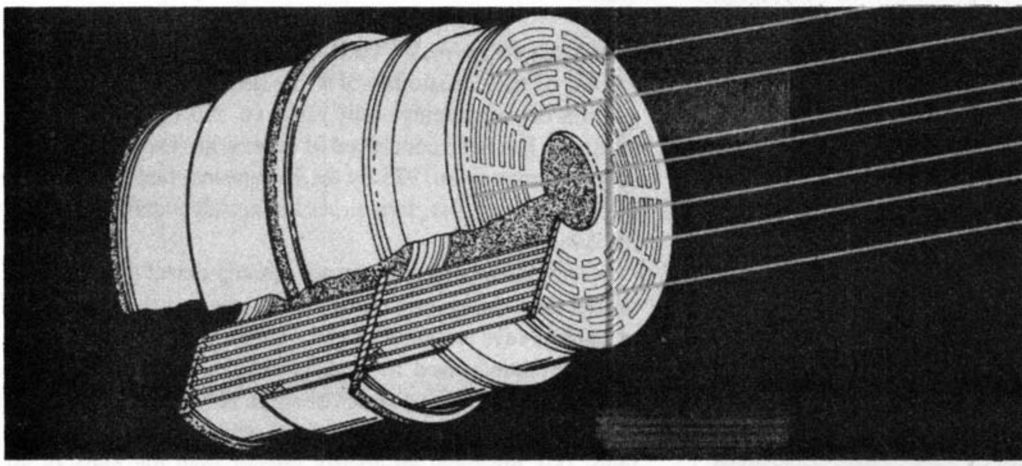
Future space-based telescopes will be actually built in space. Twenty- to thirty-meter mirrors are already being talked about, to be built in segments and assembled in space or to be built entirely in space. One proposal is to blow a large bubble of viscous liquid, attach it to some support and let it set with solar heat or ultraviolet radiation. The bubble would be aluminized and cut in half to make two mirrors. The bubble might also be left whole and filled with a low pressure gas to form a lens. It might have an aperture of 100 meters and a focal length of 100 million meters.

Ultraviolet—320 to 10 nm

Although 400 nm is the cutoff point where the eye no longer perceives the blue end of the spectrum, the real starting point for satellite ultraviolet astronomy is 320 nm, where the ozone layer begins to absorb strongly. For this reason UV astronomy is mainly space-based. The 0.8-meter Copernicus UV telescope was launched in 1972 and operated for nine years. It was joined by the International Ultraviolet Explorer (IUE) in 1978. Although smaller in aperture than the Copernicus, the IUE incorporated more efficient detectors, allowing it to see fainter objects.

FIGURE 8

The heart of the Advanced X-Ray Astrophysics Facility



Incoming x-rays are received and reflected at a grazing incidence by six nested pairs of cylindrical mirrors, and brought to focus at a distance of 10 meters.

State-of-the-art UV detectors use microchannel plates. Thousands of 1 mm glass tubes are arranged in a parallel array. An incoming UV photon enters one of the tubes, knocking loose an electron. This electron travels only a short distance before hitting the channel wall, releasing a few more electrons. A voltage difference guides the growing electron shower down toward a phosphorescent screen, where they cause the screen to glow at a small point. The screen is then photographed from behind. A newer version digitizes the output directly by attaching a resistive anode below the channels. The overall gain in output is on the order of 100,000 electrons for each UV photon.

The majority of UV sources are thermal, such as the photospheres of extremely hot stars (10,000-100,000° K). The corona and chromosphere of the Sun, and presumably of most other stars, are strong UV emitters, being at a temperature over 1,000,000° K. UV telescopes are most often used not for imaging, but for spectral studies, since carbon and nitrogen in particular are best observed in UV. Some of the most interesting work is in detecting heavy elements in novas and supernovas.

The Space Telescope, because it has a precision mirror that can work at wavelengths down to 115 nm, will provide the next technological advance in UV detection. For the extreme ultraviolet (EUV), the United States has designed the EUV Explorer, and Britain also has an extreme ultraviolet telescope that will be launched with a German x-ray telescope.

X-ray—10 to .01 nm

The well-known penetrating property of x-rays rules out all the telescope shapes used in longer wavelength astronomy. The typical x-ray wavelength is of the same order of magnitude as the atoms that make up a focusing surface, so most x-rays will just pass through or interact with the mirror surface. On the other hand, even though they are penetrating, x-rays do not penetrate very far into the atmosphere, so x-ray astronomy must be space-based.

The earliest x-ray telescopes did not attempt to focus x-rays. They were simply proportional counters, similar to Geiger counters. Incoming x-rays pass into a gas-filled chamber, ionizing some of the gas atoms. Two grids with a high-voltage differential would then guide the liberated electrons toward one of the grids. Because of the high energies involved, 30 initial electrons might generate 300,000 free electrons by the time they reached the second grid. The induced current at the detector grid would then be measured for both strength and impact position. A collimating grid placed over the front of the proportional counter limits the field of view to about one degree; beyond this crude masking, there is no way to resolve an x-ray source with this type of detector.

A new type of reflecting telescope was designed by an American team led by Riccardo Giacconi. Using a geometry first developed by a German, Hans Wolter, this telescope works by focusing x-rays using a grazing incidence angle. The overall shape is basically cylindrical, with the upper and lower portions of the walls shaped slightly differently. An incoming x-ray hits a reflector of parabolic shape at a very shallow angle and is then reflected down to a hyperbolic surface that further reflects the x-ray down to a focal point. By nesting several of these cylinders, enough x-rays can be gathered at the focus to create an image. Even so, the efficiency is only a few percent (see **Figure 8**).

The Einstein Observatory, which used this design, had several interchangeable detectors at the focus. Two were spectrometers and two were imagers. The Imaging Proportional Counter had a wide one degree field of view with a resolution of 1 arc minute. Objects of interest that required greater resolution were examined with the High Resolution Imager (HRI), which had only a 25-arc-minute field of view and a resolution of 2 arc seconds, comparable to visible light telescopes. The HRI combined two microchannel plates, which generated 10 million electrons per x-ray, with two fine grids.

The next x-ray satellite is being built by the Germans and will have a threefold increase in sensitivity over the Einstein. NASA plans to launch the Advanced X-Ray Astrophysics Facility (AXAF) by the mid-1990s, which will be five times more powerful than the German instrument.

The principal x-ray objects of investigation are the coronas around stars, interacting binary stars (most notably the suspected "black hole" candidates), and intergalactic clouds of gas.

Gamma rays—.01 to 0.000000001nm

All of the constraints of x-ray astronomy also hold for gamma-ray astronomy, only more so. No type of focusing telescope has been conceived of at present. The COS-B telescope, launched in 1975 by the Europeans, had a resolution of only two degrees, four times the apparent diameter of the full Moon.

Gamma-ray detectors do not directly detect gamma rays; rather, they depend on our understanding of the interaction of gamma rays with matter and, in that respect, are closer to the instruments used in particle physics experiments. The COS-B detector was a series of spark chambers, interleaved with layers of tungsten. Gamma rays with a wavelength shorter than .001 nm have an energy greater than the mass of an electron-positron pair. If a gamma ray in this energy range passes close to the nucleus of a heavy element, such as tungsten, it will generate pair formation. The spark chambers record their passing through the instrument and a scintillation detector at the bottom stops them and records their total energies. The path of the original gamma ray can be inferred by averaging the paths of the positron and the electron through the spark chambers, and thus the position of the gamma-ray source can be roughly calculated.

Not only is resolution poor, but the intensity is also a problem. A bright source such as the Crab Nebula will be detected at a rate of 2 or 3 photons an hour, while a weak source might generate only one photon-capture a day.

Thus far, the only known way to radically increase the "aperture" of a gamma-ray telescope is to use the entire atmosphere of the Earth as a detector. Incoming gamma rays produce flashes of light at particular wavelengths and optical telecopes can be used to collect and count these events. Since the telescope is only being used as a light bucket, the surfaces do not have to be very precise. In India, in fact, a group at the Tata Institute is using army surplus search light reflectors in a large array for this type of high-energy gamma-ray detection. The highest energy gamma-ray ever detected using this technique had a wavelength of only 0.000000001 nm!

The dedication of national resources to pushing back the frontiers of knowledge makes our nation worth defending. In that sense, conquest of the astrophysical frontiers is more fundamental than national defense itself. The people of the United States continue to cherish that frontier impulse, even while their representatives in Congress seem to have suppressed it within themselves.