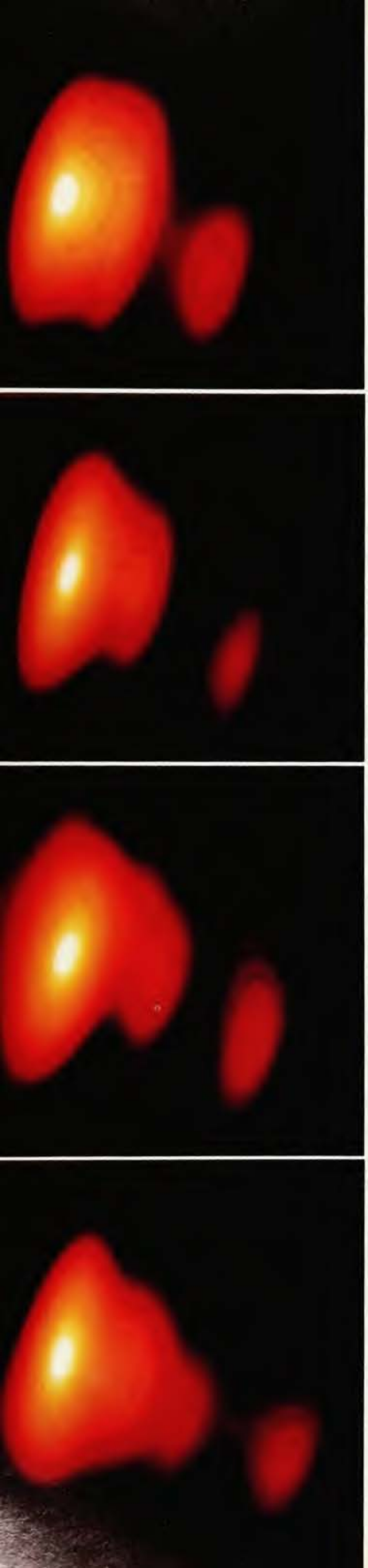


# Astronomy and

**NAS's Astronomy Survey Committee has identified priorities for new facilities that can take advantage of the tantalizing research opportunities in this decade.**

George B. Field

Astronomy is in a golden age. Discoveries since 1960 include quasars (1963), the cosmic microwave background radiation (1965), pulsars (1967), neutron-star binaries (1970), superluminal expansion of radio sources (1971), solar coronal holes (1973), evidence for gravitational radiation from a binary pulsar (1974), anomalous solar neutrino flux (1976), a super gamma-ray burst (1979), and a gravitational lens (1979). Radio, infrared, ultraviolet, x-ray, and gamma-ray techniques have made it possible to study phenomena not accessible to optical astronomy alone. Physics has come to play an increasingly important role in providing both the technology for these developments and the theoretical framework for astronomy. Today, atomic, molecular, nuclear, and plasma physics are indispensable tools in interpreting astronomical data; cosmology and the study of superdense configurations depend on general relativity and, increasingly, elementary-particle physics.

The US has played an important role in the development of astronomy in the last 20 years, a role made possible by the substantial Federal funding of ground-based research by NSF and of space-based research by NASA. The major astronomical facilities constructed in the 1960s and 70s were recommended by two National Academy studies: the Whitford Report (1964) and the Greenstein Report (1972). A new Academy report, prepared by the Academy's Astronomy Survey Committee, addresses the situation in the 1980s. The committee concludes that challenging new opportunities will arise in the 1980s as astronomers investigate the large-scale structure of the Universe, the evolution of galaxies, the nature of violent events ranging from stellar flares to quasar explosions (figure 1), the formation of stars and planets, the cause of solar and stellar activity, and the existence of planets and life beyond the solar system. A unified theory of elementary particles and of gravitation would have profound implications for cosmology.

**Images of quasar 3C273** made with the Very Long Baseline Interferometer at a wavelength of 6 cm. Images were obtained over a three-year period at intervals of approximately one year. The distance between two blobs in the image increases over this period from 62 light years (top) to 87 light years in the most recent photo (bottom). The rate of angular displacement of the blobs corresponds to eight times the speed of light, assuming a cosmological distance for 3C273. (Courtesy M. Cohen, Caltech.) Figure 1

We expect that a number of new techniques, such as submillimeter-wave astronomy, will be exploited; rapid advances in detector technology will enhance data-gathering at all wavelengths; long-lived observatories in space will open the whole electromagnetic spectrum to systematic study (figure 2); new optical and electronic technology will enable large ground-based telescopes to be built at reasonable cost; and increased computer power will permit the construction of increasingly sophisticated theoretical models of astrophysical systems. Such new technology will enable frontier problems to be attacked in the 1980s with a high degree of effectiveness and at reasonable cost.

## Frontiers of astrophysics

Here are some of the scientific opportunities for astronomy that the Committee identified.

**Galaxies and the Universe.** General relativistic models require a density singularity at the beginning of time—the big bang. Radiation from the big bang was first detected at a wavelength of 7 cm in 1965 by Arno Penzias and Robert Wilson; its thermal spectrum and its isotropic distribution have subsequently been verified. Predictions of the cosmic abundances of deuterium and helium nuclei, based upon the study of nuclear reactions occurring in the first three minutes, have been confirmed by optical telescopes on the ground and by ultraviolet telescopes in space. Although the big-bang model has passed important observational tests, in its simple version it does not explain the existence of stars and galaxies—gas simply expands out of the singularity

0031-9228 / 82 / 040046-07 / $01.00 

# astrophysics for the 1980s

in a uniform cloud. Theorists believe that galaxies and clusters of galaxies (figure 3), are the consequence of large-scale low-amplitude waves in the early Universe. It is, however, not apparent how to explain the vast intergalactic "holes" recently discovered by astronomers using digital detectors to measure the redshifts of large numbers of galaxies.

Although the measured rotational velocities of galaxies show that gravitational fields remain strong in their outlying parts, the starlight observed from such regions is very faint. The material that must be there cannot consist of stars like those at the centers of galaxies. Most likely, the matter is in the form of vast numbers of low-mass stars too faint to observe, but it is not yet possible to rule out that the mass is in the form of neutron stars, black holes, or even massive neutrinos (if they exist). Whatever its nature, "hidden mass" makes up most of the mass of Universe.

The last two decades have brought a wealth of information about active galactic nuclei. Originally discovered as pointlike optical sources in the nuclei of certain spiral galaxies (called Seyfert galaxies), they were later found to emit radio waves by the synchrotron process; active nuclei have been found in elliptical galaxies as well (figure 4). It is suspected that quasars are really hyperactive galactic nuclei. Certain types of Seyfert galaxies and quasars have similar optical spectra, and both are almost always powerful x-ray sources, encouraging the belief that they may have a similar underlying cause. Current models based on the rapid x-ray variability envision a black hole of about $10^8$ solar masses, accreting about 10 solar masses per year, and generating up to $10^{13}$ solar luminosities, largely in the form of relativistic particles, within a region 10 times the size of the solar system. It is a mystery how the gravitational energy of the inward-falling matter is converted to the energy of relativistic particles.

**Stars.** Our understanding of stellar evolution is based largely upon optical spectra of stars. Slow contraction to the main sequence, where the core consumes its hydrogen, rapid expansion to become a giant as helium burns to carbon and then oxygen, and loss of the stellar envelope, forming a planetary nebula and a white-dwarf core—all these processes have been studied by optical astronomers. But the birth of a star from an interstellar molecular cloud proceeds at such low temperatures that the radiation produced is in the radio and infrared parts of the spectrum, which require newer technologies to study.

Some molecular clouds contain dense cores in which very young stars are embedded. Study of various molecular lines in the millimeter-wave region reveals temperatures, densities and motions in such cores; some are collapsing on a time scale of about $10^6$ years. The powerful infrared sources observed in some cores appear to be young stars immersed in the cocoon of gas and dust out of which they recently formed. Radiation from the young star energizes the infalling material, repelling it at high speed; analysis of the motions surrounding the Kleinmann–Low source (figure 5) in Orion suggests that the new star is only 2000 years old.

The new ultraviolet space observatories, such as *Copernicus* and the International Ultraviolet Explorer, have revealed that many relatively cool stars exhibit the same uv features that on the Sun are emitted by active chromospheric regions, while the Einstein x-ray satellite discovered that stars of all classes are enveloped in million-degree gas analogous to the solar corona. During the 1970s solar physicists used a variety of instruments, particularly those on Skylab, to demonstrate that solar activity is entirely controlled by magnetic fields, and very possibly caused by them; thus, the presence of chromospheres and coronas on other stars implies they too have magnetic fields. These discoveries have given new impetus to attempts to understand the origin and dissipation of solar magnetic fields.

Studies of neutrinos from the Sun provide crucial tests of our understanding of stellar evolution. During the 1970s, an experiment to detect solar neutrinos found that no more than a third of the predicted neutrino flux is actually recorded, forcing a reexamination of the theory of the interior structure of the Sun and other stars.

Toward the ends of their lives, as nuclear fuels run out, stars become prone to instability. Stars of intermediate mass lose their outer layers, forming planetary nebulae. More massive stars may undergo collapse when their fuel is exhausted. If the collapse stops at nuclear densities, a neutron star is formed; if not, a black hole. Pulsars are believed to be neutron stars formed in this way; hundreds of pulsars have been found since their discovery in 1967. The discovery in 1974 of a radio pulsar in a binary system permitted the mass of the neutron star to be determined from the binary orbit; the value, 1.4 solar masses, falls within the mass range predicted by theory. Equally important was the discovery that the two components are slowly spiralling inward, apparently a result of the emission of gravitational radiation predicted by General Relativity.

If the neutron star is in orbit around a normal star, mass transfer leads to x-ray emission, first elucidated by the UHURU x-ray satellite in 1970. Several types of activity are observed. If the neutron star is magnetic, the field channels the infalling gas to the magnetic poles where it is shocked and heated; the two hot spots create an x-ray pulsar as the star rotates. Accretion onto nonmagnetic neutron stars apparently leads, as in the case of white dwarfs, to an ever-increasing depth of material, which, when it undergoes thermonuclear explosion, produces intense x-ray bursts lasting 10 to 100 seconds. It is not yet clear whether the recently discovered gamma-ray bursts, which last a few seconds and reach extraordinary intensities, are due to a similar phenomenon. The fact that one gamma-ray burst came from the direction of a supernova remnant in the Large Magellanic Cloud suggests a neutron-star origin, but the amount of energy required to explain this burst, if it originated so far away challenges explanation.

Finally, there is the mysterious case of Cygnus X-1, a powerful x-ray source associated with a hot main-sequence star. The x-ray emission varies on all time scales down to milliseconds, but with no discernible periodicities. Doppler shifts in the spectrum of the main-sequence companion reveal that it is orbited by an object of about 10 solar masses. As this is too large a mass for a neutron star, and a compact

George B. Field is chairman of the Astronomy Survey Committee of the National Academy of Sciences and director of the Harvard–Smithsonian Center for Astrophysics, Cambridge, Massachusetts.

object is required to explain the x rays, a generally accepted explanation is that the invisible companion in Cyg X-1 is a stellar black hole. The x-rays are produced as the gas spirals into the black hole from the companion star. It would be highly desirable to obtain further information on this object, so important as a test of the basic ideas of General Relativity.

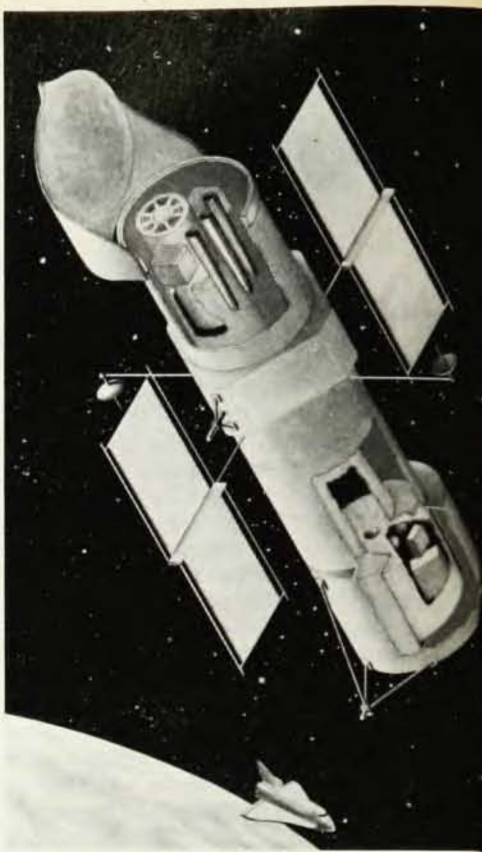
**Planets, life and intelligence.** From the perspective of the evolution of the Galaxy, the solar system is a uniquely important object. Its very existence, when taken together with the strong family resemblances observed among the Sun and many other stars, suggests that planets may be a natural concomitant of star formation. Curiously, no star has yet been shown to possess planets; a candidate case, Barnard's star, has not been confirmed.

The emergence of life on Earth appears to be unique within the solar system; however, the processes which led to it appear to be possible on any planet having the right temperature, chemical composition, and surface properties, and thus life may be widespread in the Universe if planets are common. If, as some believe, the development of intelligence is the inevitable outcome of biological evolution, intelligent beings could exist beyond the solar system. It is now technically possible to communicate all the way across the Milky Way Galaxy with such beings if they have radio technology like ours. A number of sophisticated searches for extraterrestrial intelligent signals have been conducted, so far with negative results.

### Recommended program

The Committee, through its technique-oriented panels, considered a wide range of proposed programs to address the frontiers of astronomy in the 1980s. Of these, it selected a number of new programs to recommend for funding. The Committee also identified five areas that must be strengthened as a prerequisite for undertaking new programs: instrumentation and detectors, theory and data analysis, computational facilities, laboratory astrophysics, and technical support at ground-based observatories. Significant support now exists in each area, but substantial augmentations are needed to ensure that the new programs are effective.

The Committee recommended four major new programs. Of highest priority is the Advanced X-Ray Astrophysics Facility (AXAF). An enlarged and improved version of the highly successful Einstein grazing-incidence x-ray telescope (which operated from late 1978 to early 1981), AXAF would be up to 100 times more sensitive and have up to 10 times the angular resolution (figure 2). Planned as a permanent orbiting observatory, AXAF would detect sources with x-ray luminosities as small as 1% of the Sun's total luminosity all the way across the Galaxy, study all the luminous x-ray sources in the hundreds of galaxies of the Virgo Cluster, and detect galaxies and clusters of galaxies



**Advanced X-Ray Astrophysics Facility** (AXAF), recommended as the highest-priority major new program for the 1980s. A grazing-incidence x-ray telescope with a variety of focal-plane instruments, AXAF will be a permanent orbiting observatory (Courtesy of M. Zombeck, Harvard–Smithsonian Center for Astrophysics.) Figure 2

**Hercules Cluster of galaxies**, at a redshift of 10 300 km/s (corresponding to 300 million light years), is one of many thousand known. The mechanism by which galaxies cluster in this way is somehow related to conditions in the early universe. (Courtesy of Caltech.) Figure 3

at redshifts exceeding unity, where the effects of cosmological evolution should be evident. The redshifts of clusters of galaxies can be determined from their x-ray spectra alone. AXAF will also test quasar models by detecting short-term variability.

A Very Long Baseline (VLB) Array of radio telescopes is next in priority. Using techniques based upon the recording and computer analysis of rf signals at widely spaced sites, this array, consisting of ten 25-meter telescopes, will form radio images with a resolution of $3\times10^{-4}$ arcseconds—far better than that available with any other technique. The VLB array will study the ejection of matter from quasars at relativistic speeds (figure 1), detect and analyze the motions of interstellar maser sources in regions of star formation, and measure directly the distances of objects throughout our Galaxy, and possibly in external galaxies, by determining extremely small proper motions. Because the array utilizes proven technology, it is ready to be constructed as soon as final studies of the optimum array configuration are completed.

A New Technology Telescope (NTT) of the 15-meter class on the ground, for optical and infrared observations between 0.3 and 20 microns, is given third priority. Such a facility is required because of the heavy oversubscription of the nation's available large telescopes, and because its nine-fold greater collecting area over any existing telescope will permit studies of far fainter objects than are now accessible. In particular, its large collecting area is crucial to spectroscopic studies of the extremely faint objects discovered by the Space Telescope to be orbited by NASA in 1985. Recent advances in optical and electronic technology will make its construction feasible for $100 million or less. The Committee found that the scientific merit of NTT is as high as that of any other facility considered; its lower priority reflects its state of technological readiness at this time. NTT will double the collecting area now available with the world's large telescopes, and the Committee believes that design studies of NTT should be undertaken immediately.

The fourth-priority major new program is a Large Deployable Reflector of the 10-meter class in space, designed to operate in the far-infrared and submillimeter regions of the spectrum. The Large Deployable Reflector will complement the Shuttle Infrared Telescope Facility (see below) by providing high spatial and spectral resolution on the sources discovered with the ir telescope. Thus it will be able to penetrate and resolve collapsing cores of molecular clouds and measure in detail the motions in them; it will also be a powerful instrument for the study of the structure and dynamics of planetary atmospheres.

The four major new programs recommended here—when taken together with the Very Large Array radio telescope, which was recommended by the Greenstein Committee and which went into operation in 1979, the Space Telescope (see below) also recommended by the Greenstein Committee, and scheduled for launch in 1985, and the Gamma Ray Observatory, which has been approved by Congress and is projected for launch in 1987–88—will provide the US with powerful observational capabilities across the entire electromagnetic spectrum, from gamma rays to radio waves. These capabilities can be brought to bear jointly on a host of problems; to cite but one example, quasars emit over this whole range, and each instrument contributes in a unique manner to their study.

In addition to the major programs discussed above, the Committee also recommended a number of programs of moderate cost. In rough order of priority, they are: an augmentation to the NASA Explorer program, a program which has made possible key discoveries in the past and promises to do so in the future; a far-ultraviolet spectrograph in space (FUVS), to study the important 900–1200-Å spectral range in stellar and planetary atmospheres and the interstellar medium; a space VLB interferometry antenna, to operate in parallel with the ground-based VLB array, to provide more detailed maps, greater sky coverage, and higher time resolution than can the array alone; the construction of ground-based optical-infrared telescopes in the 2–5-m class to observe transient phenomena, conduct survey and surveillance programs, provide support for space astronomy, and permit development of new focal-plane instruments; an Advanced Solar Observatory in space, to observe the Sun simultaneously at optical, extreme uv, x-ray, and gamma-ray wavelengths for long-term studies of large-scale circulation, high-energy transient phenomena, and coronal evolution; a series of cosmic-ray experiments in space, to study the interstellar medium, the origin of the elements, and violent processes on the Sun and stars; and an astronomical search for extraterrestrial intelligence, supported at a modest level, undertaken as a long-term effort, and open to the participation of the scientific community. This last project is of a different character from what is usually recognized as astronomy. While the successful detection of extraterrestrial signals would have a significance far beyond astronomy, astronomers are most familiar with the required techniques and should proceed to exploit the opportunities within this area of study during the 1980s.

The Committee also recommended four small programs chosen from a much longer list. Of highest priority within this group is a 10-meter antenna for submillimeter-wave observations; other programs of outstanding merit, which were not prioritized, are a spatial interferometer to obtain high resolution in the mid-infrared region of the spectrum, a program of high-precision optical astrometry, and a temporary program to maintain scientific expertise at US universities through a series of competitive awards to young astronomers. The Committee also recommended that seven projects not yet ready for implementation be studied during the 1980s for implementation in the 1990s and beyond.

The Committee attempted to assess the cost of the recommended program. Its very uncertain estimate (in 1980 dollars) for the total cost incurred over a decade are $190 million for the five prerequisites and $1.72 billion for the new programs. The total, about $1.9 billion 1980 dollars, can be compared with the $844 million in 1970 dollars, or $1.7 billion in 1980 dollars, for the cost of the program recommended by the Greenstein Report. As most of the Greenstein recommendations were in fact implemented, the new program recommended by the present Committee is comparable in scale to that actually carried out in the 1970s on the basis of the recommendations in the Greenstein Report.

### Ongoing activities

The new programs described above are in addition to those that are now already underway, approved for development or recommended previously by other committees, including the Space Telescope and the associated Space Telescope Science Institute; second-generation Space Telescope instrumentation; the Gamma-Ray Observatory; NASA level-of-effort programs, including research with aircraft, balloons, and rockets, as well as the Explorer and Spacelab programs; facilities for the detection of neutrinos from the solar interior; Federal grants for basic astronomical research at US universities; programs at the National Astronomy Centers; the Solar Optical Telescope and Shuttle Infrared Telescope Facility for Spacelab; and the 25-Meter Millimeter-Wave Radio Telescope.

The Space Telescope, a permanent 2.4-meter optical, uv and ir telescope in orbit, was recommended in the Greenstein Report and is under development by NASA for launch in 1985. With its 0.05-arcsecond diffraction-limited images at 5000-Å wavelength, ST will record objects nearly 100 times fainter than can be studied from the ground, and will yield images of planets with linear resolution as sharp as those of Jupiter obtained by the Voyager spacecraft. It will make possible images of distant galaxies (at redshifts greater than 0.5) as sharp as those now made from the ground of nearby galaxies; classification of the distant galaxies will permit a search for the predicted dependence of galactic properties on cosmic look-back time. The faint limiting magnitude (28) will permit studies of faint white-dwarf and red-dwarf stars near the Sun, stars near the centers of globular clusters, and bright stars in distant galaxies; its uv capability will permit new studies of hot stars, planetary atmospheres, intergalactic clouds, and quasar spectra. The Committee found that continued development of the Space Telescope is of utmost importance for all of astronomy in the 1980s.

In response to an earlier Academy recommendation, NASA has recently established a Space Telescope Science Institute to direct the ST scientific program. STScI will also serve ST users and provide the interface between the astronomical community and the ST program. The committee notes that NASA will have to carefully nurture STScI if it is to fulfill its role properly.

The Space Telescope is designed to accommodate in-orbit refurbishment and exchange of focal-plane instruments. While the instruments to be launched with ST will have powerful capabilities for optical and ultraviolet imaging and spectroscopy, second-generation insturments will be required to exploit ST's capability for two-dimensional spectroscopy and studies in the near-infrared.

The Gamma-Ray Observatory has been approved by Congress and is projected for a 1987–88 launch. Following up earlier gamma-ray surveys by NASA's Small Astronomy Satellite-2 and the European Space Agency's COS-B satellite, GRO will have much greater sensitivity and angular resolution, enabling it to study discrete gamma-ray sources, including gamma-ray bursters and the $e^+e^-$ annihilation source at the Galactic center, gamma-ray lines from recently synthesized nuclei in supernova remnants in our own and other galaxies, and variable gamma-ray emission from quasars. It will also measure the isotropy and spectrum of the gamma-ray background.

Within NASA's level-of-effort programs, balloons, aircraft, and sounding rockets remain a highly cost-effective way to explore new regions of the spectrum, test new instrumental concepts, and train students in space astronomy; they require vigorous funding. The Explorer program has provided a very effective way to carry out space science requiring substantial observation times in Earth orbit. For example, the International Ultraviolet Explorer, a collaboration between the US and Europe, has obtained nearly all the intermediate-resolution uv spectra available to the world of astronomy. The Committee endorsed three missions planned by NASA to be implemented under the Explorer program and endorsed in a previous Academy report: a Cosmic Background Explorer (COBE) to determine the spectrum and isotropy of the cosmic microwave background with high precision; the Extreme Ultraviolet Explorer, designed to open up the 100–900-angstrom wavelength range to study; and the Infrared Astronomy Satellite, an international collaboration which will survey the sky with high sensitivity in the 10–100-micron wavelength range for the first time. The Committee also endorsed a previous Academy recommendation for a new mission, the X-Ray Timing Explorer, which will study the variations of x-ray sources on time scales from milliseconds to years.

NASA has also been planning a level-of-effort program at research with the joint US–European Spacelab on the Space Shuttle. Funding of this program has not yet reached the levels required for a vigorous program of astronomical research, and the Committee urges NASA to reaffirm its original strong commitment to Spacelab.

During the 1970s, the Brookhaven experiment to detect solar neutrinos using an underground detector based on $Cl^{37}$ has accumulated data indicating that neutrinos are arriving at the Earth at a rate no more than a third of the theoretically predicted rate. It is now possible to extend this experiment by using a detector composed of gallium, which is sensitive to neutrinos of virtually all energies produced in the Sun. This is an important step, because the total neutrino production by the Sun is nearly model-independent, whereas the production of neutrinos detectable by $Cl^{37}$ depends sensitively upon the solar core temperature. Thus, any discrepancy between theory and the gallium experiment would have far-reaching implications for particle physics or astronomy or both. The Committee therefore urged the completion and operation of the gallium detector at the earliest opportunity. Experiments employing lithium and indium detectors may also become feasible during the 1980s.

**Radio galaxy 3C449**, as mapped by the Very Large Array. (The arcsecond beam of this radio telescope array is indicated by the box. The map shows oppositely-directed narrow beams of relativistic particles emerging from the nucleus of the galaxy. (Courtesy National Radio Astronomy Observatory). Figure 4

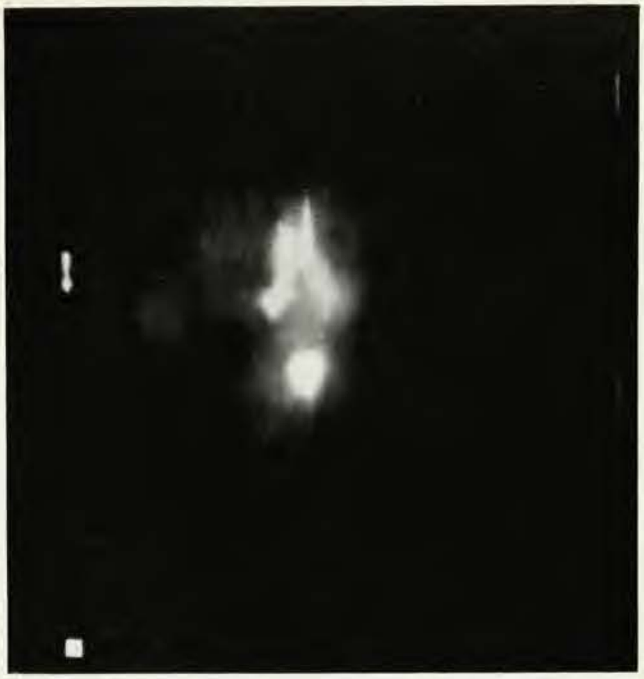
Federal grants for the support of astronomical research at universities are given both by NASA and NSF. Such grants are the lifeblood of university research, which in turn is vital to the national research program because it is the primary source of fresh young minds. The Committee recommends that the program of Federal grants to universities be continued and augmented where necessary to support the prerequisites for new research initiatives discussed earlier.

National Astronomy Centers perform a vital role in the national program by providing a diverse array of observational facilities to all qualified astronomers, independent of other sources of support. In many cases their facilities are unique and among the most powerful in the US. The Centers must be funded at a level that not only provides for the proper maintenance of facilities and staff in spite of the inroads of inflation, but also provides for the acquisition of needed new equipment in addition to the major capital expenditures recommended by the Committee.

Two facilities within the Spacelab program require special emphasis. The Solar Optical Telescope, a one-meter diffraction-limited telescope capable of resolving details as small as 14 km across on the Sun, has been selected by NASA for flight in 1987–88. SOT will enable solar physicists to study the fine-scale magnetic structure believed to be responsible for heating the solar corona, driving the solar wind, and energizing solar flares. It is to be the core of a battery of solar instruments developed under the Spacelab program, called the Solar Shuttle Facility; this in turn will provide the foundation for the Advanced Solar Observatory recommended by the Committee. The Committee urges the continued development of SOT.

The Spacelab Infrared Telescope Facility (SIRTF), a cryogenically-cooled meter-class telescope, will study the range of wavelengths from 2 to 300 microns. For certain types of observations it will be 1000 times as sensitive as the largest existing infrared telescopes, and will be able to detect infrared sources at the limits of the observable universe. SIRTF is now under study by NASA; the Committee strongly supports the recommendations of other Academy committees that SIRTF be developed as the first major infrared telescope in space.

The Greenstein Report recommended construction of a millimeter-wave telescope, then projected to have a diameter of 65 meters and a minimum operating wavlength of 3 millimeters. This facility was not funded; in the meantime the scientific requirements have moved to shorter wavelengths, and the need is now for a more precisely figured telescope operable at wavelengths down to 1 millimeter. The Committee supports the construction of a 25-Meter Millimeter-Wave Radio Telescope to fill this need. The large collecting area of the 25-m telescope will permit the detection of faint sources, and its high angular resolution will permit studies of molecules in other galaxies.



**Infrared image** of the Kleinmann–Low nebula in Orion made with a digitized scanning system at the University of Wyoming. The primary object in this region is a star estimated to be only 2000 years old; it emits over 100 000 times the luminosity of the Sun. (Courtesy R. D. Gehrz, G. L. Grasdalen, and J. A. Hackwell, Wyoming Infrared Observatory.) Figure 5

### What the programs will do

The programs recommended by the Astronomy Survey Committee will make possible astronomical research of unprecedented scope. COBE will be able to detect the minute fluctuations in the microwave background predicted by models of galaxy formation. Several instruments, including ST, NTT, SIRTF, and AXAF, will pobe the visibility of galaxies so distant that they are undergoing early phases of evolution; ST will produce sharp images of even the most distant galaxies, and because of its large collecting area, NTT will obtain their spectra and determine their redshifts. If, as theory predicts, multiple supernova explosions occur in young galaxies, AXAF can detect the x-radiation of the resulting billion-degree gas.

The extended periods of slow evolution of galaxies can be studied by ST, NTT and other instruments. Slow changes in the colors of galaxies are predicted; as massive stars are formed and die, galaxy colors should shift from ultraviolet to blue to red. Failure to detect the predicted changes will challenge the theories of galactic and stellar evolution based upon the big-bang model of the Universe. GRO will test ideas of galactic nucleosynthesis by studying gamma-ray lines in our own and possibly other galaxies.

The nuclei of active galaxies will be probed by ST, AXAF, GRO, and the VLB Array. ST will test the hypothesis that quasars are active nuclei by obtaining such sharp images that the quasar will stand out in contrast from the galaxy, and will reveal motions and structure within the active nuclei of nearby galaxies, which are not resolvable with ground-based telescopes. AXAF will obtain statistics of x-ray emission from distant quasars to test whether the as-yet unresolved x-ray background is made up of quasars, as is now suspected; GRO will carry out a similar program at gamma-ray wavelengths, at the same time testing the hypothesis that a good fraction of quasar emission is in the gamma-ray region. Theoretical models will be strongly constrained by observations of variability at both x-ray and gamma-ray energies. The VLB Array will probe active nuclei with unprecedented resolution to test theories of relativistic jets, and will study jet phenomena in much closer objects, such as SS 433, to throw light on the physics involved.

Solution of the problem of hidden mass in galaxies will be a major goal of extragalactic research in the 1980s. NTT will determine velocities of faint globular clusters on the outskirts of the Galaxy, making it possible to map its mass distribution. AXAF will test for the presence of faint red stars, which may constitute the hidden mass, by detecting the x-rays their hot coronas would inevitably emit.

Star formation will become much more accessible to study with the advent of powerful infrared facilities such as NTT, ST, SIRTF, and LDR, as well as high-frequency radio telescopes such as the 25-m millimeter telescope and the 10-m submillimeter-wave antenna. NTT will observe the dusty cocoons of young stars in the near infrared, its large aperture providing sensitivity for spectroscopy of a large number of expected molecules. Second-generation instruments on ST, orbiting above the Earth's opaque atmosphere, will reach further into the infrared. SIRTF will pick up the even longer wavelengths at which cooling the mirror is necessary to avoid background problems. LDR will cover the whole range with sufficient collecting area to do high-resolution spectroscopy. The 10-meter submillimeter-wave antenna on the ground will study molecular lines from collapsing interstellar clouds in selected wavelength windows in the atmosphere, and the 25-meter will do the same at all wavelengths greater than one millimeter. These studies will produce maps of young stars in a number of collapsing clouds and determine den-

**Image of solar corona** made with the x-ray telescope aboard the NASA Skylab mission. The confinement of the hot gases in the solar corona by the solar magnetic field is evident. (Courtesy of L. Golub, Harvard–Smithsonian Center for Astrophysics.) Figure 6

**Cassiopeia-A supernova remnant**, in an x-ray image made with the Einstein x-ray observatory. The x rays are emitted by gas heated by the passage of the supernova shock wave. (Courtesy of S. S. Murray, Harvard–Smithsonian Center for Astrophysics.) Figure 7

sities and motions of the surrounding infalling gas for comparison with computer models of star formation.

Stellar activity and mass loss are now recognized to play an important role in stellar evolution. In so-called turbulent dynamos, which are not yet well understood, thermal convection and differential rotation in stars combine to produce flux tubes of gas and magnetic fields that rise to the surface by magnetic buoyancy; there they dissipate, the energy heating a corona (figure 6) or driving away a stellar wind. A synergistic study of activity and mass loss on both the Sun and the stars will yield new insights in the coming decade. The Solar Optical Telescope will resolve details on the Sun as small as 14 km in ultraviolet images of the gases in flux tubes, and obtain ultraviolet and visual spectra of high resolution, permitting measurement of plasma velocities, densities, and temperatures. Addition of other instruments on Spacelab will permit observations at x-ray and extreme-ultraviolet wavelengths, allowing studies of all of the relevant atmospheric layers, with temperatures ranging from 6000 K to above 2 000 000 K. Eventually this collection of instruments built around SOT is expected to evolve into a free-flying Advanced Solar Observatory, which will provide such data continuously.

Astronomers will also study activity and mass loss on many other stars, having different masses, temperatures, and rotation rates from those of the Sun. Gross effects such as star spots and active regions can be inferred from ground-based optical studies, but much greater power for such studies will be furnished by ST and FUVS, which will be able to detect the ultraviolet emission lines associated with chromospheric and coronal temperatures, and AXAF, whose x-ray vision will be sensitive to coronal temperatures. Theories of stellar activity and mass loss will thus be confronted by detailed information about the Sun, as well as by integrated information about many stars whose different gross properties lead to different theoretical predictions about their activity.

Late stages of stellar evolution will continue to provide challenging problems throughout the 1980s. GRO will help answer whether gamma-ray bursts really originate in neutron stars, and if so, what is the source of the accreting matter responsible for the bursts. XTE, by providing long-term precise timing of x-ray phenomena, will enable investigations of the masses, magnetic fields, and internal structures of degenerate stars such as neutron stars and white dwarfs; the data will constrain models of accretion disks and emission regions. AXAF, by observing extremely faint x-ray sources, will permit statistical studies down to a faint limit of all the x-ray binaries in Messier 31. ST and FUVS will yield a rich array of spectroscopic information on the motions and properties of hot gas involved in mass transfer from normal stars to collapsed companions.

Studies of supernova remnants will be advanced dramatically. AXAF will delineate the gases that have been heated to one million degrees or more by supernova shock waves (figure 7), while ST and FUVS will obtain the spectra of critically important ions used for plasma diagnostics. These data, taken together with high angular resolution maps of the synchrotron radiation by relativistic electrons made by the VLA, will provide observational tests of theories of collisionless shock waves and postshock plasma turbulence in which particle acceleration occurs.

It will be possible in the 1980s to make a systematic study of the existence of planetary systems beyond the solar system. A key element in this effort will be a low-cost recommendation to fund advanced astrometric instruments that can determine stellar positions with an accuracy of one milliarcsecond, sufficient to detect Jupiter's gravitational pull on the Sun from a distance of 5 parsecs. Such a gravitational pull can also be determined spectroscopically by measuring the radial velocity of the parent star with an accuracy of a few tens of meters per second. Such accuracies are already being attained with stable high-resolution spectrographs on large telescopes.

Should there be intellient life on any planet beyond the Earth within the Milky Way galaxy, it is technically possible even now to receive radio signals generated by such life. While the probability that a planet bearing intelligent life exists is almost impossible to estimate (see PHYSICS TODAY, March page 26) the detection of such signals could conceivably teach us much about the planetary habitat.

Modern astronomy ranges from the birth of matter in the big bang to the development of life on other planets. The facilities recommended by the Committee will provide ways to attack key questions over the entire range. However, if past experience is any guide, the increase in capability provided by these facilities will reveal new phenomena of completely unexpected kinds.

* * *

*Copies of the complete report,* Astronomy and Astrophysics for the 1980s, *by Astronomy Survey Committee of the NAS may be obtained later in May from the National Academy Press, 2101 Constitution Avenue NW, Washington DC 20418.* □