New instruments for astronomy

# High-energy astrophysics

George W. Clark

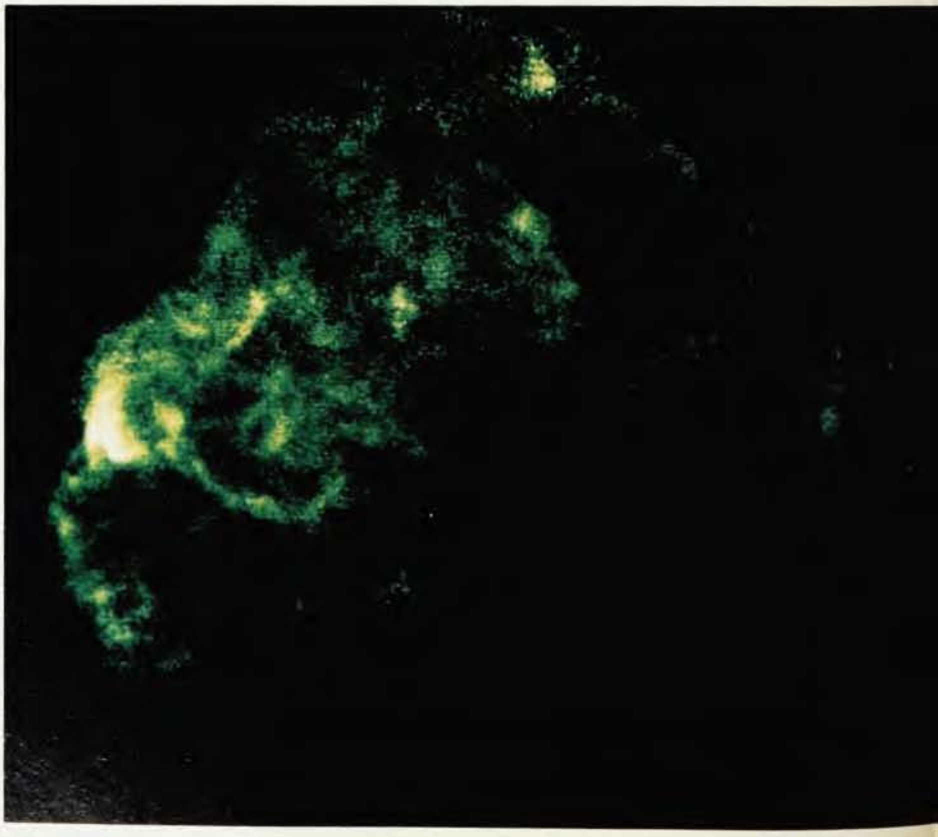
Ultra-high temperatures and densities, high-energy particles and intense gravitational and magnetic fields exist in many kinds of objects throughout the universe. During the past two decades, the origin and evolution of these conditions have become central topics of astronomy. In many instances, the conditions are so extreme as to be unattainable in terrestrial experiments; astronomical observations are thus a unique source of empirical information about the physical processes that occur under these circumstances. Much of the information is obtained from observations of x rays, gamma rays, and energetic electrons, nuclei, neutrons, and neutrinos. These, together with gravitational radiation, have come to be considered the province of "high-energy astronomy."

The High Energy Astrophysics Panel of the Astronomy Survey Committee examined the current status and future prospects of high-energy astronomy, with its broad range of instrumental and interpretative techniques, in six areas of specialization, namely x rays, extreme ultraviolet radiation, gamma rays, cosmic rays, neutrinos and gravitational waves. In addition, the panel considered high-energy solar astronomy, with results that parallel those of the Solar Working Group (see page 60) and need not be included here.

All areas of high-energy astronomy benefited from large improvements in observational capabilities during the 1970s. For example, the orbiting Einstein x-ray observatory, launched in 1978, achieved in one step a hundred-fold increase in sensitivity over previous x-ray observations and, for the first time, brought high-resolution spectroscopy to bear on the analysis of conditions in cosmic plasmas. Exploratory euv observations showed that interstellar space is far more transparent to soft x rays and the extreme uv than had been previously thought, thereby offering the promise of new information about the coronae of nearby stars and about the interstellar medium from euv observations by future satellites. Several dozen discrete sources of high-energy gamma rays were discovered where only the galactic and extragalactic components of the diffuse gamma-ray background were previously known. Satellite-borne cosmic-ray detectors achieved sufficient precision and resolution in the measurement of mass and charge of energetic particles to permit the use of various isotope "clocks" in the study of the acceleration and propagation of high-energy nuclei in the Galaxy. Gravitational-wave detectors achieved a ten-fold increase in amplitude sensitivity, and there are clear prospects for future detectors with sufficient sensitivity to assure the detection of gravitational waves from known cosmic processes, provided the general theory of relativity is correct. The measurements of neutrinos from thermonuclear reactions in the Sun's core have been refined, but the results are not consistent with expectations based on the standard theoretical explanation of how energy is generated within the Sun.

Much of the progress in the 1970s was the outcome of programs recommended by the previous decade's Astronomy Survey as laid out in the Greenstein Report. The most ambitious of these was the series of three High-Energy Astronomy Observatories, which were launched by NASA near the end of the decade. The first of these was an all-sky x-ray survey with large-area mechanically collimated detectors, the second was the Einstein Observatory, and the third a cosmic-ray and low-energy gamma-ray observatory. The Einstein Observatory, in particular, established x-ray astronomy as a source of astronomical information comparable in importance to radio and optical astronomy.

In spite of the breadth and significance of the results obtained from these pioneering US activities in the 1960s and 1970s, there will be little activity in high-energy astronomy through most of the 1980s due to reductions in



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**Astrophysical observations of high-energy photons and particles enable us to study states of matter under conditions far more extreme than will ever be found in an Earth-bound laboratory.**

funding, which have delayed, terminated or precluded new projects. The only substantial observational capabilities in x-ray astronomy during most of the decade will be those of the Japanese and European space programs. The early promise of opportunities for frequent and comparatively inexpensive experiments via the Space Shuttle has not been realized, and with NASA's attention now turning to the establishment of a permanently staffed orbiting facility, the scientific support capabilities of the Shuttle may never be more than marginally utilized.

If the nearly ten-year gap in US activities in space-based high-energy astronomy is not to stretch well beyond the 1980s, it is essential that major new programs be initiated soon, and that the few already underway be carried through without further delay. The most important of current projects is the Gamma-Ray Observatory, which is intended to extend the work of the US and European Explorer-class high-energy gamma-ray missions of the 1970s. GRO has survived several close brushes with cancellation and is now under construction for a projected launch in 1988. A second project of major importance, approved by NASA for a new start but not yet underway, is the Extreme Ultraviolet Explorer. Predicating its conclusions on the assumption that these two projects will be carried through, the panel made specific recommendations for five major new programs:

▶ Construction of a permanent orbiting Advanced X-Ray Astrophysics Facility

▶ Long-duration, in-orbit exposures of large instruments for definitive cosmic-ray measurements

▶ Development of instruments for solar astronomy in the Spacelab program with the aim of incorporating them in an eventual Advanced Solar Observatory

▶ An augmentation of the Explorer Satellite program to permit the launch of high-energy astronomy satellites at a rate of one every two years

▶ Development of advanced instrumentation for x-ray astronomy for eventual deployment on major Shuttle-launched facilities.

The panel also made recommendations for five smaller programs:

▶ Continuing support of neutrino observations, including international collaboration in development of a gallium detector to measure the rate of a fundamental mode of solar energy production

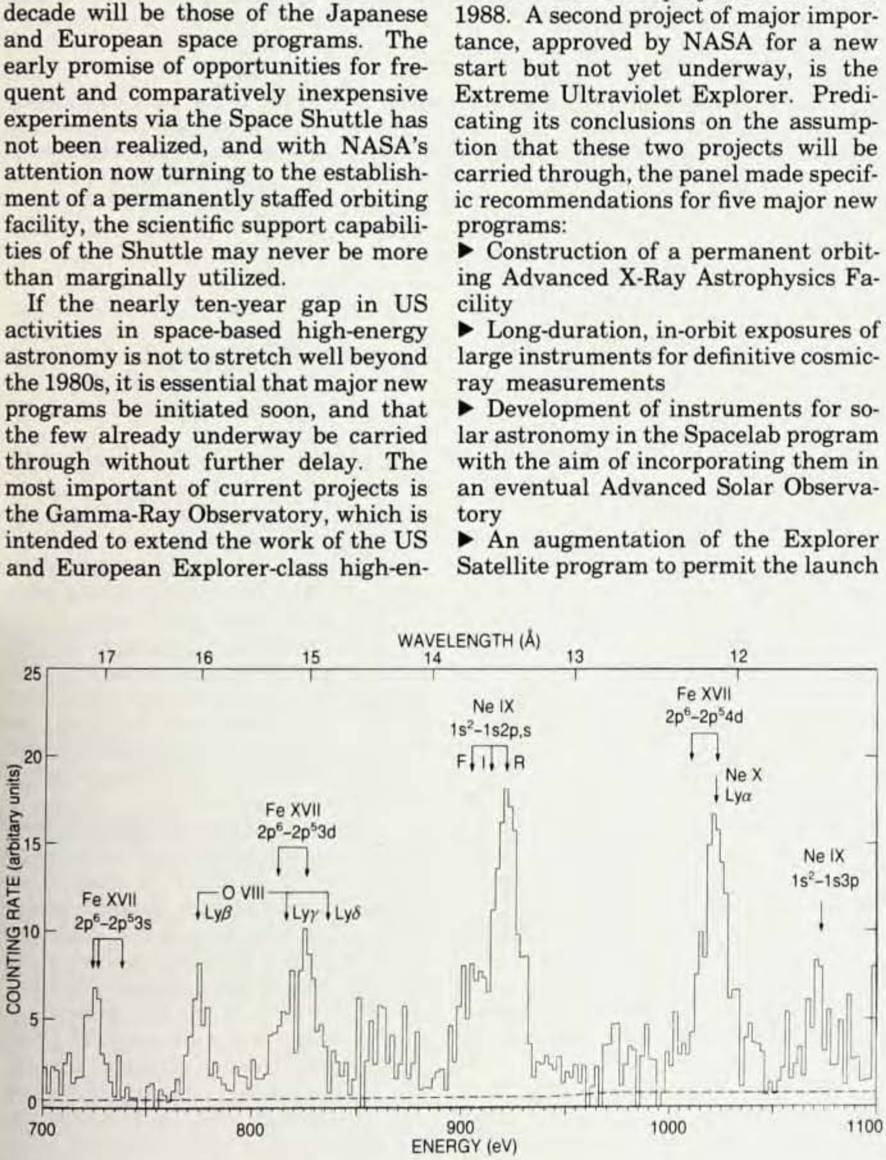
▶ Support for development and deployment of detector systems for gravitational waves

▶ Establishment by NASA of a program for theoretical high-energy astrophysics appropriately related in scale to the effort in observational high-energy astronomy

▶ Maintenance of scientifically productive programs of rocket and balloon experiments in high-energy astronomy

▶ Support of air-shower studies aimed at elucidating the origin and propagation of the highest-energy cosmic rays.

These recommendations grew out of extensive discussions with specialists in each of the six fields mentioned above. Let us now examine them in more detail and in the context of the considerations that led to them.

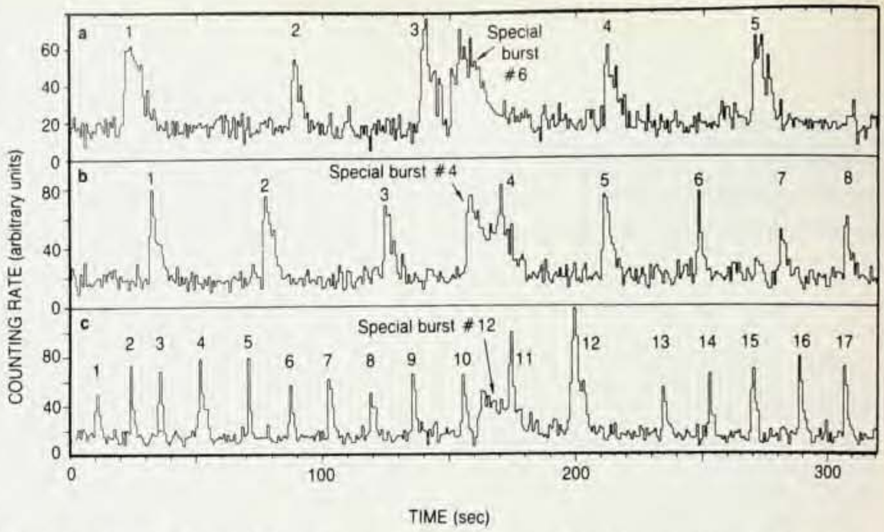



**Puppis supernova remnant:** x-ray image (left) and spectrum (above). The image is a mosaic of smaller images recorded by the high-resolution imager of the Einstein X-Ray Observatory. The spectrum was obtained with the Bragg-reflection focal-plane crystal spectrometer. Analysis of the relative intensities of the x-ray emission lines demonstrates that the material of the remnant has temperatures in the range 2–5 $\times 10^6$K and an abundance ratio O:Fe 3–5 times the cosmic value. (Spectrum from reference 7) Figure 1

### X-ray astronomy

The first extrasolar x-ray source, Sco X-1, was discovered in 1962. By the end of the 1960s, exploratory investigations with rockets and balloons had found about three dozen more discrete x-ray sources. Only a few of these had been identified with visible counterparts: six with supernova remnants, two with faint variable stars, one with the Crab pulsar, and one with an extragalactic source, the giant radioemitting elliptical galaxy M87. In addition, an unresolved and apparently diffuse x-ray background had been observed. On the theoretical side, the idea that x-ray stars, such as Sco X-1, are neutron stars in close binary systems accreting matter from their normal nuclear-burning companions had been advanced however, no proof of this conjecture existed. It was also becoming clear that x-ray emission is the principal energy-loss mechanism of supernova remnants and that, therefore, x-ray observations provide a powerful approach to the study of their evolution as they interact with the interstellar medium. Detection of x rays from M87 gave promise that one could discover other "x-ray galaxies" with more sensitive observations, and that fundamentally new aspects of galactic dynamics, associated with x-ray sources far more powerful than x-ray stars or supernova remnants, might be revealed. Thus the future of x-ray astronomy looked promising, although its impact on many of the fundamental problems of stellar and galactic evolution was still comparatively slight.

The situation began to change rapidly in 1970 with the launch of Uhuru, the first of several small x-ray satellites that included the British Ariel V, the Small Astronomy Satellite SAS-3, and the Japanese Hakucho (currently the only non-solar x-ray observatory in operation). The Orbiting Solar Observatories 7 and 8, the Copernicus UV Observatory, and the Astronomical Netherlands Satellite also carried x-ray instruments. These satellites provided the means to obtain deep exposures both scanning the sky and pointed at individual objects, and this advantage translated into large improvements in sky coverage, sensitivity, positional accuracy and spectral resolution. These observations extended the catalog of x-ray sources to hundreds of objects, including various kinds of single stars and binary systems, supernova remnants, active galactic nuclei and clusters of galaxies. The x-ray observations had their greatest impact in the study of close binary systems that contain a neutron star or black hole, and in the study of clusters of galaxies containing intergalactic gas that emits x rays. Rocket and balloon observations also made important contributions, specially in the exploration of the soft x-ray background and in observations of hard x-rays from discrete sources. The satellite HEAO-1 extended this work to fainter sources with detectors of larger area and broader spectral range. Finally, the Einstein Observatory, HEAO-2, carrying the first image-forming satellite-borne x-ray telescope for nonsolar observations, brought hundreds of thousands of objects within the range of x-ray detection. It provided high-resolution images of point-like and extended sources, and facilitated detailed analyses of emission lines in x-ray spectra. These advances demonstrated that x-ray observations are relevant to nearly every area of contemporary astrophysics. Moreover, the operational success and scientific impact of the Einstein mission and the wide participation of astronomers in the use of the observatory through its guest observer program demonstrated the usefulness and feasibility of a permanent orbiting national x-ray observatory to obtain x-ray data of a quality comparable to the radio data from the Very Large Array and the optical–uv data expected from the Space Telescope.




**Variation in x-ray intensity** from the Rapid Burster as recorded by the SAS-3 x-ray observatory. Data from three different 5-minute intervals show many "type II" bursts (numbered sequentially) of x-ray emission from blobs of plasma that fall to the surface of the neutron star from a region in which matter drawn from a nearby companion star is stored. Each of these intervals also shows a "type I" (special) burst due to thermonuclear flash in the material accumulated on the surface of the neutron star. (From reference 8.) Figure 2

Concepts for new US x-ray missions have been developed with an eye on x-ray satellite activities abroad—in particular, preparations for new and larger Japanese x-ray missions, the anticipated launch this year of the European Space Agency's EXOSAT on the Ariane rocket, and development of the German x-ray observatory ROSAT to be launched by the Space Shuttle in 1986. EXOSAT will have a guest observer program open to non-Europeans. ROSAT will have imaging capabilities comparable to that of the Einstein telescope by virtue of a high-resolution imager to be supplied by NASA; in exchange for the launch on the Space Shuttle, it will be made available to US astronomers for a substantial fraction of its expected life after the first six months.

Achievement of many important scientific goals will require new orbiting facilities for x-ray astronomy. For example

▶ To understand how the energy of rotation and internal motions of stars is transformed into coronal heat we must study systematically the relations between coronal x-ray emission and other stellar properties in stars of all types

▶ For better knowledge of the structure of neutron stars, and of the flow of plasma in their intense magnetic and gravitational fields we will need long-term observations of binary x-ray sources with detectors of very large sensitive area

▶ To understand the dynamical evolution of supernova remnants and their interaction with the interstellar medium we need spatially resolved high-resolution spectra of many remnants at levels of sensitivity substantially higher than previously available

▶ Measurements of the properties and location of binary x-ray sources in the thousands of galaxies in the Virgo Cluster will shed new light on the formation and evolution of stars under the wide variety of conditions in spiral and elliptical galaxies

▶ More detailed knowledge of the composition and distribution of hot intergalactic gas in clusters of galaxies is needed to clarify how clusters evolve

▶ A more sensitive x-ray telescope with improved angular resolution can help determine the nature of the unresolved isotropic x-ray background.

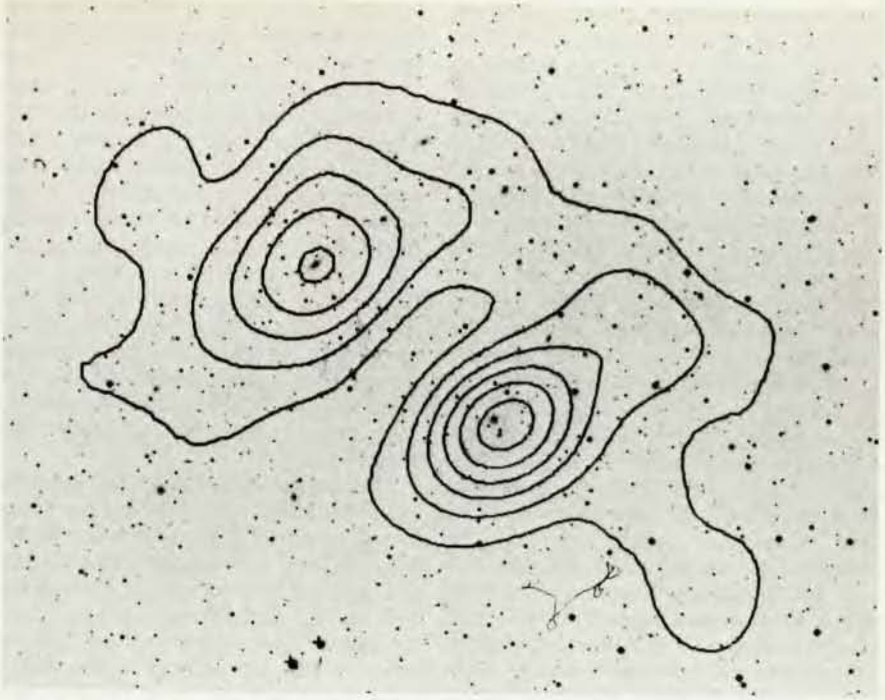
Thus there is a wide range of interesting astrophysical problems accessible to x-ray observations. Moreover, one can be sure that the new observatories required to reach these and other specific goals will produce exciting surprises, as did every one of the exploratory x-ray missions of the 1970s.

The key component of the future US program in x-ray astronomy is the Advanced X-Ray Astrophysics Facility, which is planned to have a grazing-incidence reflection telescope with a diameter of 1.2 m and a focal length of 10 m capable of forming images with 0.5-arc-second resolution in the energy range from 0.1 keV to 8 keV. With an effective area of 1500 $cm^2$ at 0.6 keV and 250 $cm^2$ at 6 keV and with state-of-the-art image detectors, AXAF will achieve a hundred-fold increase in sensitivity over the Einstein Observatory in the detection of point sources. Focal-plane instrumentation will provide a range of capabilities for spectrometry and polarimetry that will far surpass in sensitivity and resolution anything previously available. AXAF will be able to study clusters of galaxies at distances corresponding to a redshift of $z = 3$ and quasars as luminous in x rays as 3C273 at $z = 10$. Iron K-line emission from intracluster gas should be detectable in clusters at $z = 2$, thereby providing an independent x-ray measure of redshift distance. These distances equal or exceed those at which such objects can be studied at other wavelengths by the Space Telescope and the VLA, and they are large enough to assure that major evolutionary effects will be observed if current ideas about the origin of the universe in the Big Bang are correct.

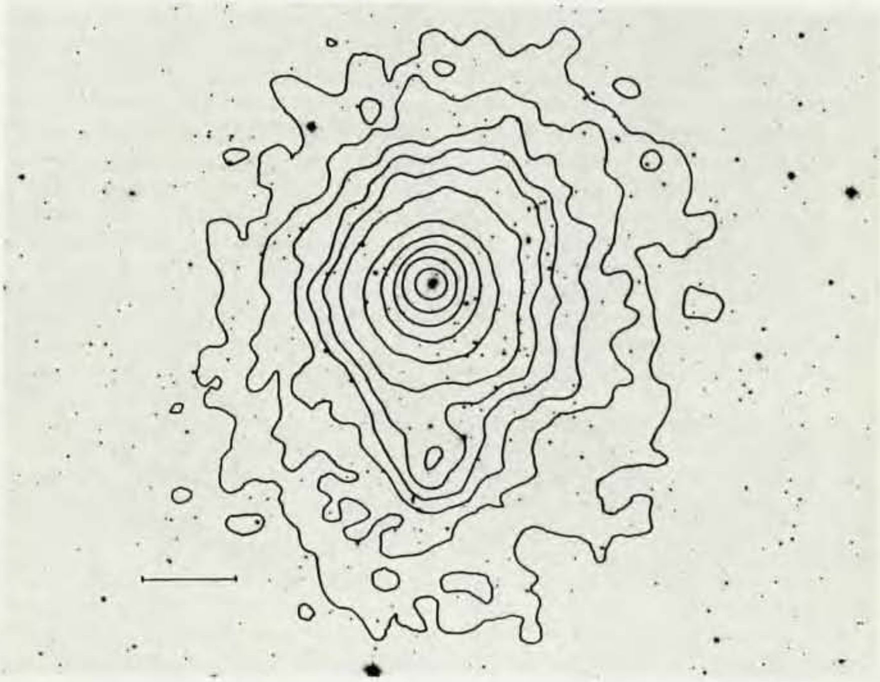
All of the technology required for AXAF is within the current state of the art. Moreover, the Einstein Observatory served, in effect, as a prototype that demonstrated the feasibility of all the basic concepts of x-ray telescopy involved in AXAF. Careful estimates have shown that its cost will be about three-quarters of that of the Space Telescope. Recognizing that the tasks of scientific planning, operations and management of the AXAF after launch will be comparable in scope to those anticipated for the Space Telescope, the Panel recommended that an institutional arrangement resembling the Space Telescope Science Institute be established for AXAF in time for it to provide effective scientific guidance during development of the facility and its data system.

The panel recommended two other large x-ray observatories for early development: a Large Area Modular Array of Reflectors and a large X-Ray Observatory. The large-area array is a multi-mirror modular telescope system that would provide very large effective area (about $3 \times 10^4$ $cm^2$ at 2 keV) with modest angular resolution (10–60 arc seconds, depending on position in the field of view) at comparatively low cost. Among its purposes would be to discover, characterize and identify very faint sources in sky surveys, to provide detailed image analysis of extended sources with low surface brightnesses, to measure variability in quasars and other distant compact sources and to carry out moderate-resolution spectroscopic studies of distant sources to derive redshifts from x-ray emission-line measurements. The other large proposed X-Ray Observatory would be aimed at problems outside the capabilities of AXAF and the large-area modular array. Examples of these problems are sensitive polarimetry of compact sources and supernova remnants and the spectroscopic study of faint galactic and extragalactic sources in the energy range above 10 keV, where one finds spectral features related to cyclotron resonances of electrons in the intense magnetic fields of neutron stars.

Smaller x-ray satellites for specialized studies that complement or supplement the observing programs of the large observatories are vitally important to the renewal of strong university-based programs in x-ray astronomy in the US. These must be free-flying satellites of the so-called Explorer class, launched by the Shuttle or by independent means. Concepts for several such satellites have been put forward, and among these the Panel designated the X-Ray Timing Explorer



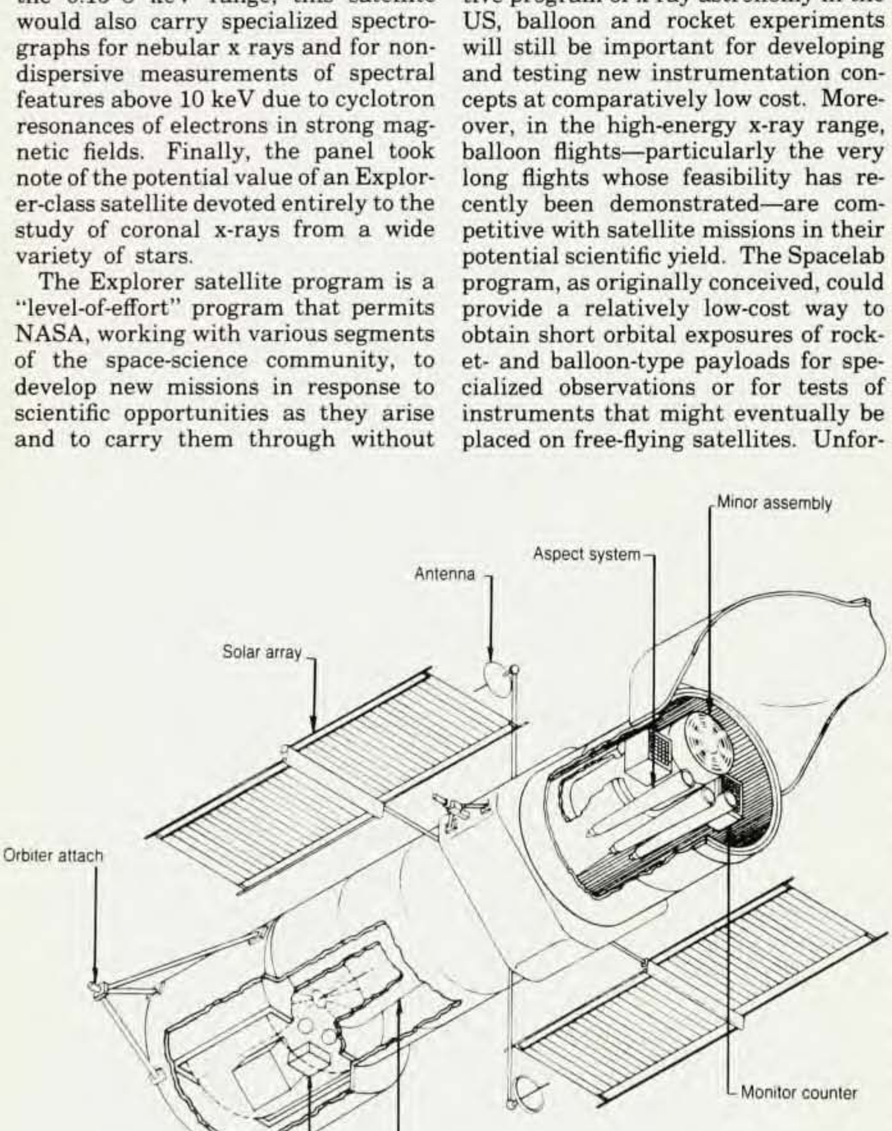
**Images of hot intergalactic gas** in two clusters of galaxies as recorded by the x-ray imaging proportional counter on the Einstein Observatory. The x-ray intensity contours correspond to the gravitational potential contours. Their shape reveals that SC 0627-54, (above) having no dominant central galaxy, is less dynamically evolved than A85 (below), which does have a massive central galaxy (Courtesy of W. Forman). Figure 3



as the small satellite mission of highest priority in x-ray astronomy. With a sensitive area of 1 $m^2$ and spectral response above 2 keV, XTE would be used to study compact galactic x-ray sources to investigate, for example, the properties of condensed matter in neutron stars and white dwarfs, the physics of accretion flows in intense gravitational and magnetic fields and the mechanisms of x-ray bursts and other transient phenomena. Other important proposed Explorer missions are the Soft X-Ray Explorer with imaging and spectroscopic capabilities in the 0.1–1.5 keV range, and an X-Ray Spectroscopy Explorer for specialized long-exposure spectroscopic analysis of stellar coronae, x-ray binaries, supernova remnants and clusters of galaxies in the 0.15–8 keV range; this satellite would also carry specialized spectrographs for nebular x rays and for non-dispersive measurements of spectral features above 10 keV due to cyclotron resonances of electrons in strong magnetic fields. Finally, the panel took note of the potential value of an Explorer-class satellite devoted entirely to the study of coronal x-rays from a wide variety of stars.

The Explorer satellite program is a "level-of-effort" program that permits NASA, working with various segments of the space-science community, to develop new missions in response to scientific opportunities as they arise and to carry them through without specific Congressional approval of individual missions. In spite of the remarkable scientific productivity of the program, its effectiveness in recent years has been eroded by inadequate funding. The resulting slowdown in new starts and in support of post-mission data analysis has had a particularly severe impact on research and graduate teaching in the space sciences at universities. The last x-ray explorer, SAS-3, was launched in 1975, and the next one, XTE, will not be launched until 1987 or later. In view of this, the Panel recommended an augmentation of the Explorer budget to allow one new start in high-energy astrophysics every two years.

Though free-flying satellites must be the foundation for renewal of a productive program of x-ray astronomy in the US, balloon and rocket experiments will still be important for developing and testing new instrumentation concepts at comparatively low cost. Moreover, in the high-energy x-ray range, balloon flights—particularly the very long flights whose feasibility has recently been demonstrated—are competitive with satellite missions in their potential scientific yield. The Spacelab program, as originally conceived, could provide a relatively low-cost way to obtain short orbital exposures of rocket- and balloon-type payloads for specialized observations or for tests of instruments that might eventually be placed on free-flying satellites. Unfortunately, the technical and fiscal constraints that currently exist in the Spacelab program have severly curtailed its use in astronomy.




**Advanced X-Ray Astrophysics Facility** after deployment by the Shuttle Transportation System. AXAF has been designated as the highest priority new project in US astronomy for the 1980s by the Astronomy Survey of the National Academy of Sciences. (Courtesy of Marshall Space Flight Center.) Figure 4

### Extreme ultraviolet astronomy

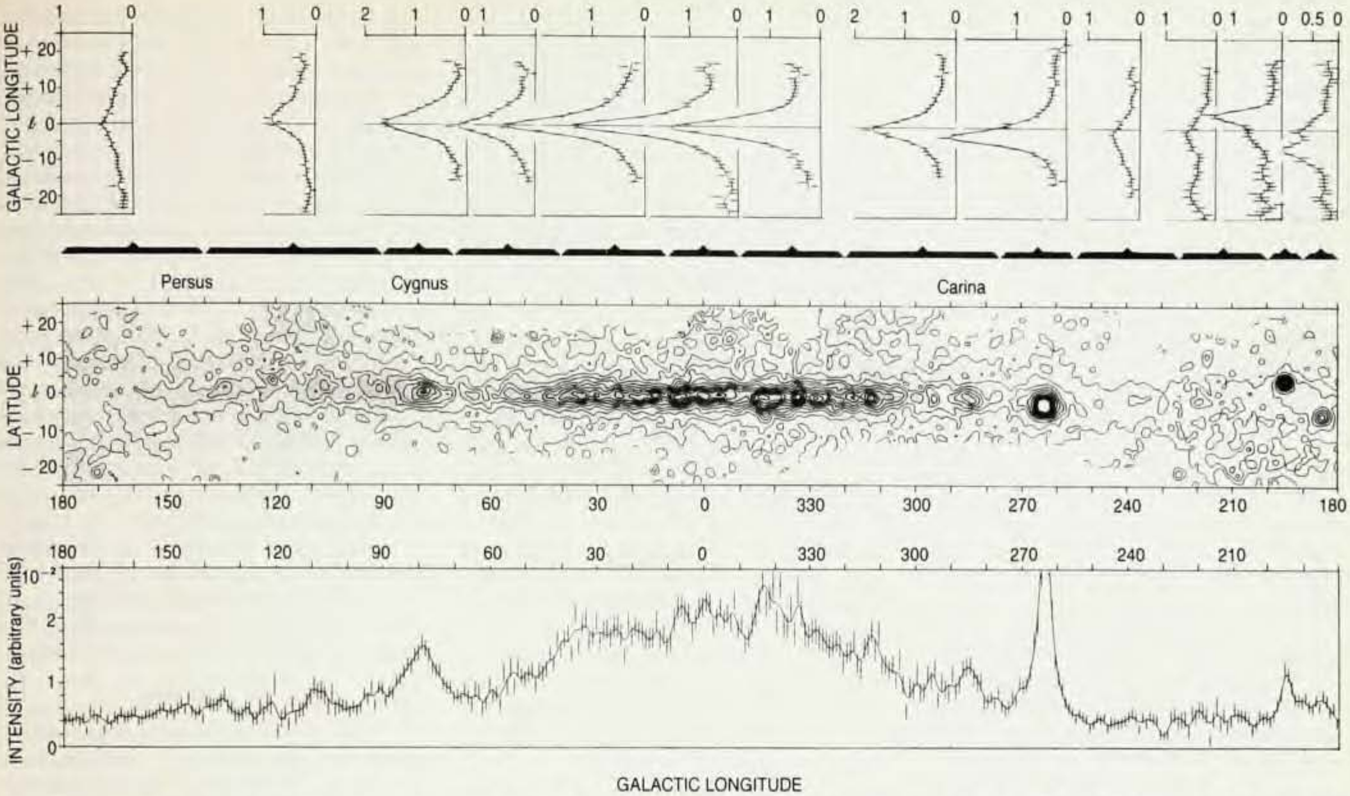
Rapid growth in empirical and theoretical knowledge of the interstellar medium during the 1970s resulted in a dramatic improvement in the prospects for euv astronomy in the spectral range from 100 to 1000 angstroms: The transparency of the interstellar medium at euv wavelengths is much greater than previously believed. Observations along some lines of sight out to distances of 300 parsec or more are possible, and it is clear that a large number of stars can be studied in the euv. Thus we can now hope to undertake, for example, comparative studies of stellar chromospheres, examinations of transition regions and coronae in stars of many types, analyses of euv phenomena in white dwarfs in accreting binary systems, studies of single hot white dwarfs to determine the physical processes involved in their cooling, and further probes of the structure and state of the local interstellar medium.

The essential next step in the development of this nearly virgin field of observational astronomy is the flight of the Extreme Ultraviolet Explorer, approved by NASA for a new start in 1981, but still not in construction due to the underfunding of the Explorer program. Even before the flight of the EUVE, it is clear that detailed high-resolution spectroscopic measurements of euv sources will be needed next. The Panel recommended that adequate support be given to the development of instruments for such measurements and for their testing in rocket flights.

### Gamma-ray astronomy

Discovery of the galactic and extragalactic components of an unresolved flux of high-energy (more than 50 MeV) gamma rays in the 1960s stimulated the development of two Explorer-class gamma-ray satellites in the 1970s, SAS-2 by NASA and COS-B by the European Space Agency. Both achieved greatly improved angular resolution and sensitivity through the use of multiplate spark chamber detectors. They mapped the intensity of diffuse high-energy gamma rays and discovered numerous discrete sources, mostly concentrated along the Milky Way. The catalog compiled from COS-B data contains several dozen sources or concentrated source regions and includes the quasar 3C273, the Crab pulsar, the x-ray binary Cygnus X-3, and some gamma-ray "hot spots" attributed to the interactions of cosmic rays with matter in dense interstellar clouds.

Interesting results at lower energies were also obtained. For example, a




**High-energy gamma-ray emission** (in the energy range 70 MeV to 5 GeV) observed in survey of sky by the COS-B satellite of the European Space Agency. The middle panel is a strip map centered on the galactic equator with isointensity contours; the contour intervals are at $3\times10^{-3}$ on-axis counts per sec per steradian. The brightest of 24 sources or concentrated source regions is the Vela Pulsar (PSR0833-45) at galactic longitude 263°.5. The top panel shows latitude profiles averaged over the ranges of longitude indicated by the adjacent brackets. The bottom panel is the longitude profile of the intensity averaged over the range of galactic latitude from $-5°$ to $+5°$. (From reference 3.) Figure 5

slowly variable flux of ½-MeV gamma rays from positron annihilations was detected from a source in the direction of the galactic center. Bursts of low-energy gamma rays were discovered, and though their cause is still unknown, the isotropy of their arrival directions is generally believed to indicate a very local origin. The spectra of the bursts show evidence of redshifted annihilation lines and cyclotron-resonance features, suggesting that they are produced near the surfaces of magnetized neutron stars. The most remarkable gamma-ray burst of all was one of exceptional brightness and unusual form that occurred on 5 March 1979. After an initial brief spike with a millisecond rise time it exhibited a relatively low-intensity decay phase with 8-second pulsations. The position of its source, determined with arc-minute precision from a comparison of the arrival times of the burst at detectors on various spacecraft located around the solar system, was found to coincide with the remnant of a supernova in the Large Magellanic Cloud. If the source is in fact related to that remnant and if it radiated the burst isotropically, then its instantaneous luminosity at the peak of the burst exceeded the total continuous luminosity of our Galaxy at all wavelengths.

At very high energies, ground-based Čerenkov-light detectors have detected air showers produced by gamma rays with energies above $10^{11}$ eV from the Crab pulsar, Cygnus X-3, and the radiogalaxy Centaurus A.

Gamma-ray astronomy provides unique information on a wide variety of problems such as the mechanisms of pulsar radiation, the distribution of high-energy particles in the Galaxy, the processes in nuclei of active galaxies and the origins of the high-energy background radiation. The recent discoveries of spectral features have opened new possibilities for the study of the composition and physical state of matter in gamma-ray sources. The nature of gamma-ray burst sources remains a challenge to future observations and theory. Thus a vigorous effort in gamma-ray astronomy over the entire range of energies from $10^5$ eV to greater than $10^{11}$ eV is an essential part of future high-energy astrophysics.

The Gamma Ray Observatory, now under construction and scheduled for launch near the end of the decade, will carry gamma-ray telescopes for observations in the energy range from $10^4$ eV to $2\times10^{10}$ eV. The sensitivities of the GRO instruments will surpass those of previous detectors by at least an order of magnitude over the entire energy range, and their angular resolutions will be substantially better. The observatory will be equipped to study the properties of gamma-ray bursts and to accomplish spectroscopy of gamma-ray emission lines. Thus the GRO will facilitate detailed analytical studies of many of the known astronomical gamma-ray phenomena, and it will have the capability to extend exploratory observations far beyond any previous mission.

Looking beyond the GRO, the panel saw the need for a specialized Explorer-class mission devoted to the detailed study of transient gamma-ray sources. They are probably the sites of the most extreme conditions of high temperature and pressure that occur anywhere in the Universe. A Gamma-Ray Transient Explorer would include a hard x-ray all-sky monitor to provide essential survey data and a hard x-ray detector with a high-resolution collimator for measuring the positions of the sources of gamma-ray bursts with accuracies of about 1 arc minute, sufficient to ensure good chances for identifying their optical counterparts. It would also have high-resolution spectrometers to measure the energy and shapes of emission lines and cyclotron-resonance features.

Research in gamma-ray astronomy above $10^{11}$ eV has been dormant for several years in the US. The Panel recommended that it be revived with the development and use of more sensitive ground-based facilities.

### Cosmic-ray astronomy

High-energy astronomy began with the discovery of cosmic rays in 1908. For the first time it was realized that radiation other than visible or near-visible light arrives at Earth from outer space. Cosmic rays were evidently a form of high-energy radiation with a penetrating power greatly exceeding that of any of the then-known natural or artificial radiations.

We now know that the primary cosmic rays constitute a suprathermal gas of high-energy charged particles that pervade the Galaxy. They consist mostly of protons, alpha particles and other bare nuclei with energies from a few MeV to more than $10^{14}$ MeV. High-energy electrons constitute about 1% of the total cosmic-ray flux, and antiprotons and positrons, produced in collisions of cosmic rays with interstellar matter, are present in trace quantities.

The composition and energy spectra of cosmic rays carry information about their sources and the mechanisms of their acceleration and propagation. Cosmic rays are also an important astrophysical entity in themselves, with an energy density comparable to that of the interstellar magnetic field and of the turbulent motion of interstellar gas. The pressure of cosmic rays and the heat generated by their collisions with interstellar matter affect star formation and influence the evolution of the Galaxy. Detailed knowledge about the properties of cosmic rays is therefore essential to an understanding of galactic dynamics.

In recent years various satellite and balloon instruments have been developed that can measure the relative abundances of individual isotopes of the elements from hydrogen to iron, and of individual elements up to the uranium. These advances are very significant for our understanding of the Galaxy; for example from the relative abundances in cosmic rays of the various stable and unstable isotopes produced in the sources or in collisions with interstellar matter one can deduce the mean containment time of cosmic rays in the magnetic field of the Galaxy and the mean thickness of the interstellar matter they traverse between their sources and the Earth. Current values for these quantities are about $10^7$ years and 7 g/cm$^2$, respectively, which implies that the mean density of matter along the paths traversed by cosmic rays is significantly less than the mean density of matter in the galactic disc. It is interesting to note also that differences between the isotope and element abundances in cosmic rays and in the Sun show that solar and cosmic-ray material have distinctly different histories of nucleosynthesis.

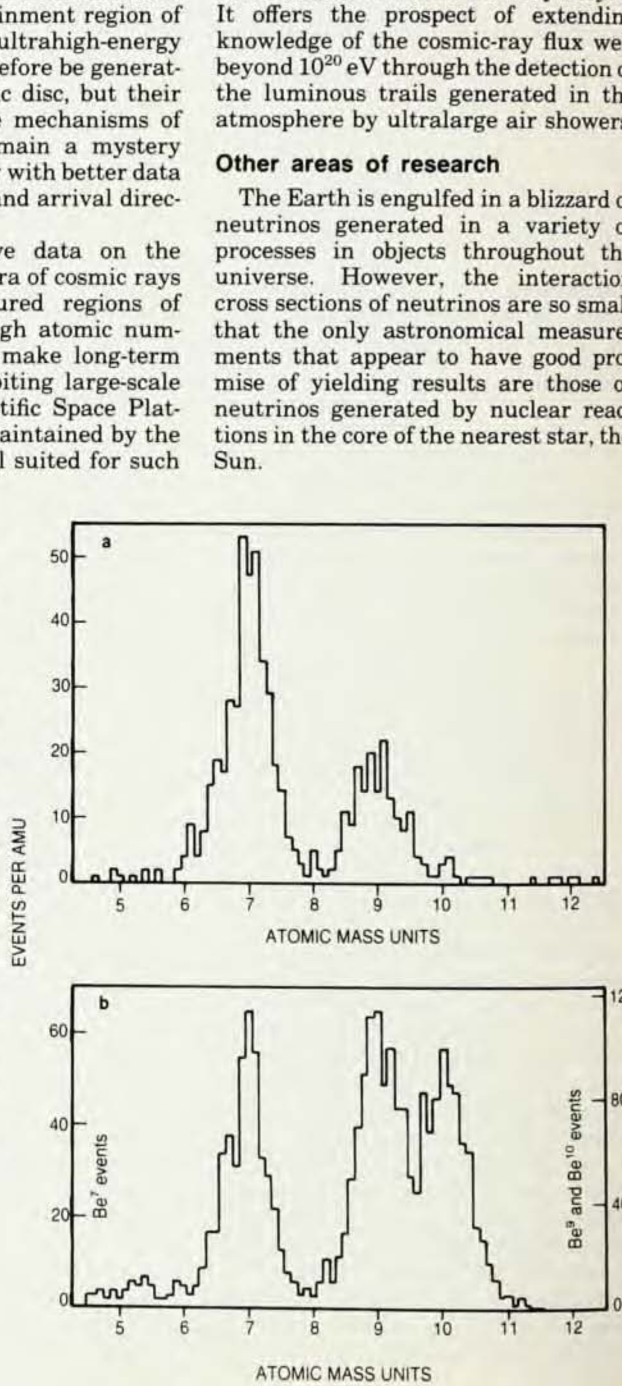
Measurements of the primary electron spectrum reveal a steepening above 30 GeV attributable to in-flight energy losses acting for a mean containment time that is also about $10^7$ years. Furthermore, the low proportion of positrons shows that most cosmic-ray electrons are not produced in collisions between cosmic-ray nuclei and the interstellar medium but are directly accelerated.

Measurements of air showers produced by cosmic rays have extended our knowledge of the spectrum and arrival directions of cosmic-ray nuclei to above $10^{20}$ eV where the radii of curvature of the primary particles in the galactic field exceed the dimensions of the magnetic-containment region of the Galaxy. These ultrahigh-energy cosmic rays must therefore be generated outside the galactic disc, but their actual origin and the mechanisms of their acceleration remain a mystery that can be solved only with better data on their composition and arrival directions.

To obtain definitive data on the composition and spectra of cosmic rays in the poorly measured regions of higher energy and high atomic number, we will need to make long-term observations from orbiting large-scale instruments. A scientific Space Platform, launched and maintained by the Shuttle, would be well suited for such measurements. The panel recommended that cosmic-ray instruments for such a mission be developed and tested in Spacelab flights, and then transferred to a Space Platform for 1 to 2 years. The techniques for such instruments are already well developed and have been tested in balloon flights or in the HEAO-3 mission. Of particular importance to our understanding of the influence of cosmic rays on the interstellar medium is the measurement of the composition and spectra of very-low-energy cosmic rays outside the solar cavity. This will require the use of special instruments on deep-space probes. Finally, the panel urged support of the promising new approach to air-shower measurements embodied in the instrument called the "Fly's Eye." It offers the prospect of extending knowledge of the cosmic-ray flux well beyond $10^{20}$ eV through the detection of the luminous trails generated in the atmosphere by ultralarge air showers.

### Other areas of research

The Earth is engulfed in a blizzard of neutrinos generated in a variety of processes in objects throughout the universe. However, the interaction cross sections of neutrinos are so small that the only astronomical measurements that appear to have good promise of yielding results are those of neutrinos generated by nuclear reactions in the core of the nearest star, the Sun.




**Mass distribution of beryllium isotopes** in cosmic rays (top) and in beryllium produced by spallation from an accelerator beam of nitrogen (bottom). Because the relative abundance of Be in cosmic rays is high compared to its general cosmic abundance, cosmic-ray Be is believed to be almost entirely the result of spallation from interactions of cosmic-ray nitrogen nuclei with interstellar matter. The absence of Be$^{10}$ (halflife of $1.5 \times 10^6$ yrs) in cosmic rays therefore implies that the average containment time for cosmic rays in the galaxy is greater than $10^7$ years. (From reference 9.) Figure 6

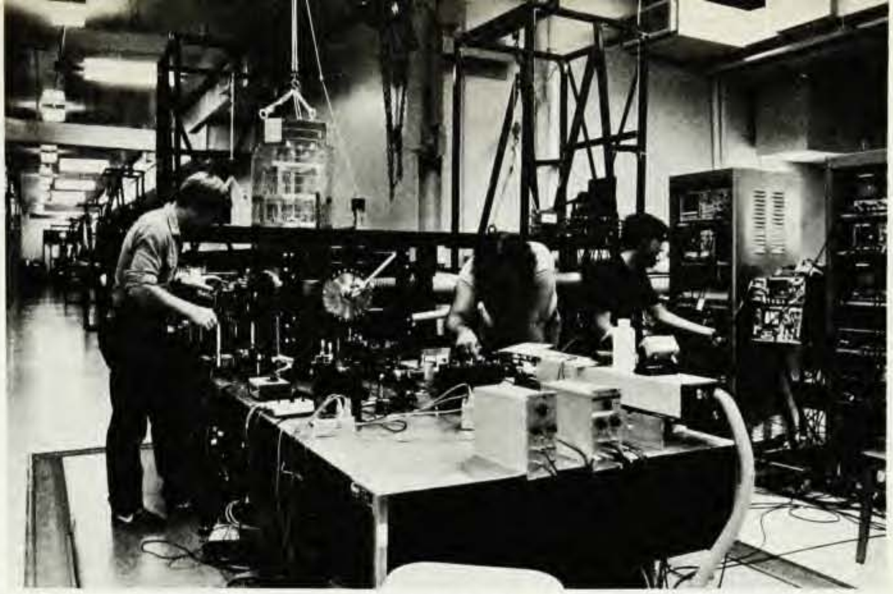
Physicists made remarkable progress during the 1970s in measuring the flux of low-energy solar neutrinos through radiochemical analysis of the products of neutrino interactions in 100 000 gallons of chlorinated hydrocarbon in a tank one mile underground. The measured counting rate in the experiment was about 0.5 per day, implying a solar neutrino flux of $2.2 \pm 0.4$ solar neutrino units instead of the value of 7.8 snus predicted by the standard model for the Sun. In view of the profound consequences that this apparent contradiction between prediction and observation may have for the theory of thermonuclear power production in the Sun and other stars, the panel recommended support of a proposed international collaboration to carry out a new experiment based on the radiochemical detection of neutrino reactions in 50 tons of gallium.

The gravitational collapse of a star into a neutron star or black hole is expected to produce a brief, intense burst of neutrinos in the intermediate energy range 10–50 MeV. Several detectors now in operation or under construction may be able to observe such a neutrino burst from a stellar collapse. The panel encouraged support of this work although it recognized that very long observation may be required to register even one event.

**Gravitational waves** are predicted by the general theory of relativity. They are expected to be radiated by spherically asymmetric relativistic bulk motions of the kind that would occur if two massive black holes at the center of some galaxy coalesced. If such waves could be detected and measured, their characteristics would provide a critical test of general relativity and unique information about their sources and the processes that generate them.

It has been estimated that gravitational waves from the brightest conceivable events might cause strains in a detector amounting to values of the dimensionless strain parameter $h$ of $10^{-16}$. On the other hand, it appears likely that gravitational waves from any of a variety of plausible events frequently cause strains for which $h$ is on the order of $10^{-21}$, which would change the Earth–Sun distance by only 1 Å. These estimates serve to define the problem which confronts gravitational-wave astronomy.

The effort to detect gravitational waves was greatly stimulated in the early 1970s by reports of positive results from a detector with a strain sensitivity near $10^{-16}$. By 1980, improved versions of the same kind of detector—superisolated massive bars instrumented with supersensitive strain transducers—were operating at strain sensitivities of $3 \times 10^{-18}$ with only negative results. Negative results at similar sensitivities but broader frequency bandwidths have been obtained with multireflection laser interferometers having arm lengths of 1 m to 40 m. Other negative results of less sensitivity were obtained by gravimetric monitoring of the Earth's quadrupole vibrations and Doppler tracking of deep-space probes. Meanwhile, the close agreement between the measured rate of orbital decay of the binary radio pulsar and the rate predicted according to General Relativity has provided the only empirical evidence for the existence of gravitational radiation.



**Multi-beam interferometric gravitational-wave detector** with a 40-m baseline under construction at Caltech. When fully operational it is expected to have a strain sensitivity of better than $10^{-18}$ at $10^3$ Hz. (Courtesy of Stanley Whitcomb.) Figure 7

Recognizing the great potential value of gravitational-wave detection, in a sense the last frontier of observational astronomy, the Panel recommended that the efforts to improve both bar and laser interferometer instruments be adequately supported with the aim of achieving sensitivities of $10^{-20}$ by 1990. The latter appear, at present, to offer the greatest promise of success in the long run when a kilometer-scale laser interferometer system may be constructed.

The ultimate system for gravitational-wave detection may be laser tracking of one spacecraft by another over solar-system distances. Sensitivities of $10^{-21}$ at all frequencies from 30 to $10^{-4}$ Hz might be achieved, and gravitational waves from a variety of sources would then almost certainly be detected.

**Theoretical research.** Throughout its discussions, the Panel was concerned with the need to ensure that adequate support be provided for theoretical research related to the problems of planning and interpreting observations in high-energy astronomy. In the past, much of the progress in creating the intellectual framework for understanding the discoveries and analytical results of high-energy astronomy has been supported by funds derived from the portions of satellite projects allocated to data analysis. Such mission-oriented support tends to lack flexibility of purpose and long-term continuity. At the same time, it seems clear that there should exist some proportionality between the amount of observational activity in a field such as high-energy astronomy and the level of effort committed to related theoretical research. Therefore, the panel recommended that high priority be given to providing new funding for theoretical research in high-energy-astrophysics at a level commensurate with the total task of interpreting the results of observational programs, but independent of specific missions or observational programs.

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