

SPACE ASTRONOMY AND ASTROPHYSICS

A revitalized program with a balance of large, moderate and small missions, frequent access to space and improved scientific management will lead to major advances in our understanding of the universe.

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and Blair D. Savage

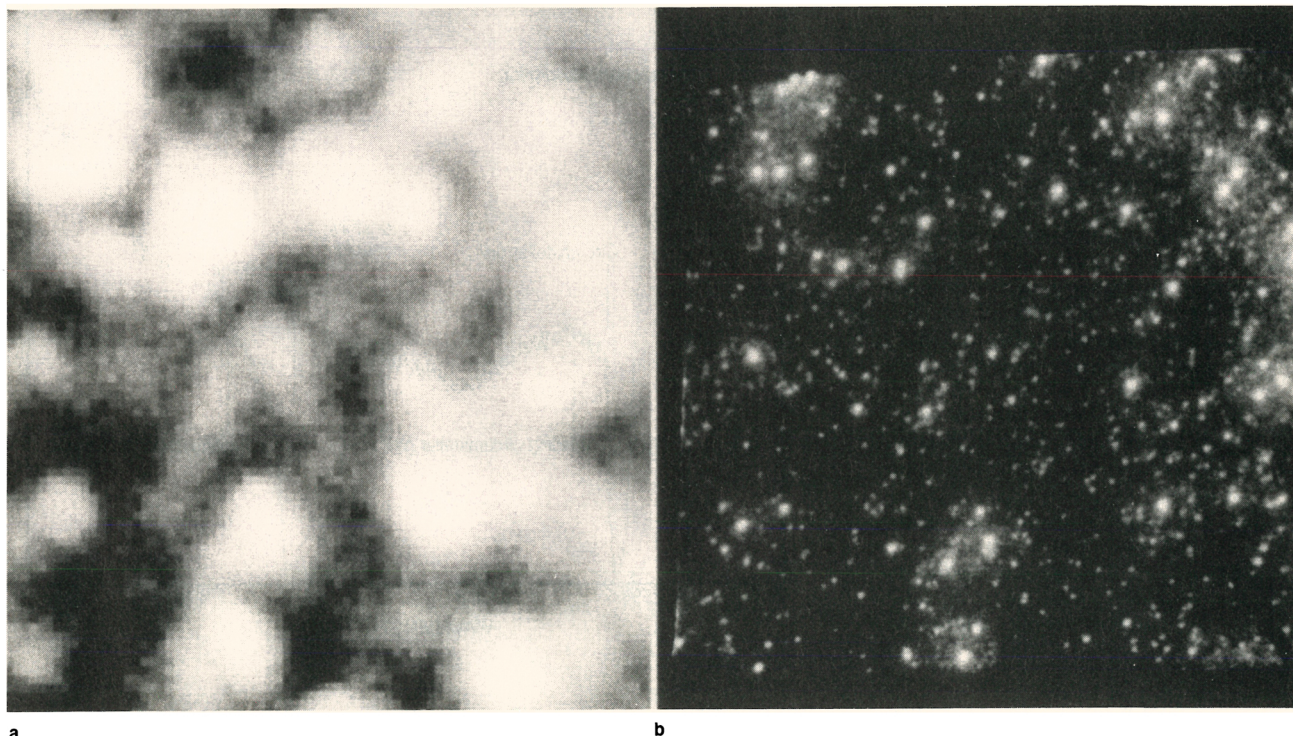
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Nearly everything we know about the cosmos comes from studying celestial electromagnetic radiation over roughly 16 decades of wavelength from radio to gamma ray. But most radiation is totally absorbed by our atmosphere—only radio and optical waves penetrate to Earth, and even these are subject to distortion or interference. The ability of space astronomy to escape the effects of Earth's atmosphere has literally opened new windows on the heavens, windows through which we have glimpsed a universe far more diverse than previously known and tantalizingly rich with information about its structure and evolution.

The report of the Astronomy and Astrophysics Survey Committee recognizes the tremendous potential of space astronomy for further discovery and for addressing fundamental questions of astrophysics, ranging from nucleosynthesis in the Big Bang to the detection of planetary systems. The committee chose the Space Infrared Telescope Facility as its highest-priority large initiative, highlighted opportunities for major advances through an accelerated program of moderate and small missions and addressed questions of program balance, infrastructure and policy.

A decade of elation, then frustration

The decade of the 1970s was a heady time for NASA and space astronomy. Building on the tentative explorations of the 1960s, astronomers launched a progression of satellites that carried increasingly sensitive instruments. X-ray and gamma-ray missions such as the series of Small Astronomy Satellites and High Energy Astrophysics Observatories found evidence for accreting neutron stars and black holes in close binary systems, shock-heated remnants of supernova explosions, hot interstellar and intracluster plasma, ubiquitous energetic processes around quasars, coronal activity in nearly all kinds of normal stars and sudden bursts of energetic photons from sources still unknown. Ultraviolet spectrographs on the Orbiting Astronomical Observatories and the International Ultraviolet Explorer surveyed the ultraviolet properties of stars of all types, performed chemical and physical analyses of circumstellar and interstellar gas and probed the energetics of active galactic nuclei. A battery



Globular star cluster M14. Two images of a 22×22 -arcsecond region contrast ground-based and HST imaging capabilities. **a:** The image obtained at the Cerro Tololo Inter-American Observatory in Chile has an angular resolution—determined by turbulence in the atmosphere—of 1.5 arcseconds. **b:** The image obtained by the European Space Agency's Faint Object Camera aboard the HST shows, with 0.08-arcsecond resolution, a near-uv image of cluster stars. The HST image reveals hundreds of stars, whereas only dozens are apparent in image **a**. The effects of spherical aberration of the HST mirror result in the apparent "nebulosity" around the "brighter" stars. (From B. Margon, S. F. Anderson, R. A. Downes, R. C. Bohlin, P. Jakobsen, *Astrophys. J. Lett.* **369**, L71, 1991.) **Figure 1**

of x-ray and uv instruments on the Solar Maximum mission scrutinized our nearest star through the peak of its activity cycle.

By contrast, the 1980s was a time of frustration. The opening of the ir window by the Infrared Astronomy Satellite and more recently the launch of the Cosmic Background Explorer are notable triumphs. However these were the only American astronomical satellites launched in the 1980s, whereas 10 were launched in the 1970s. In some fields activity shifted to Europe or Japan, but the overall decline in scientific vitality was marked. Much of the difficulty can be traced to NASA's reliance on the space shuttle as its primary launch vehicle. The consequences of this policy, laid bare by the Challenger disaster, will continue to haunt us through most of the present decade.

Within the past 18 months, NASA has launched COBE, the Hubble Space Telescope, the German-British-US x-ray telescope ROSAT and the Astro Shuttle payload; the Gamma Ray Observatory is scheduled for this spring. Although these missions constitute part of the long-delayed program of the 1980s, they are already building a crescendo of new scientific results that should eventually drown out recriminations about their protracted development.

Released after the survey committee completed its study, the recent report by the Advisory Committee on the Future of the US Space Program,¹ chaired by Norman Augustine, spotlights many of NASA's difficulties and gives direct and sound advice on how to overcome them. The agency, together with the legislative and executive

branches of the Federal government, can seize this opportunity to correct past mistakes and build on present strengths to revitalize NASA as a whole. The space science community should be enthusiastic participants and supporters of this effort, and can endorse wholeheartedly its recommendation for "shifting the priorities of the space program to place primary emphasis on science."

Large, medium and small missions

A major lesson to be learned from the hiatus of the 1980s and from the HST is the paramount importance of a balanced program of large, moderate and small missions together with continuing efforts in technology development and in theory and data analysis. Achieving program balance was virtually impossible during the 1980s. Large and moderate missions were stranded on the ground at considerable expense, and very few small ones could be accommodated by the shuttle program.

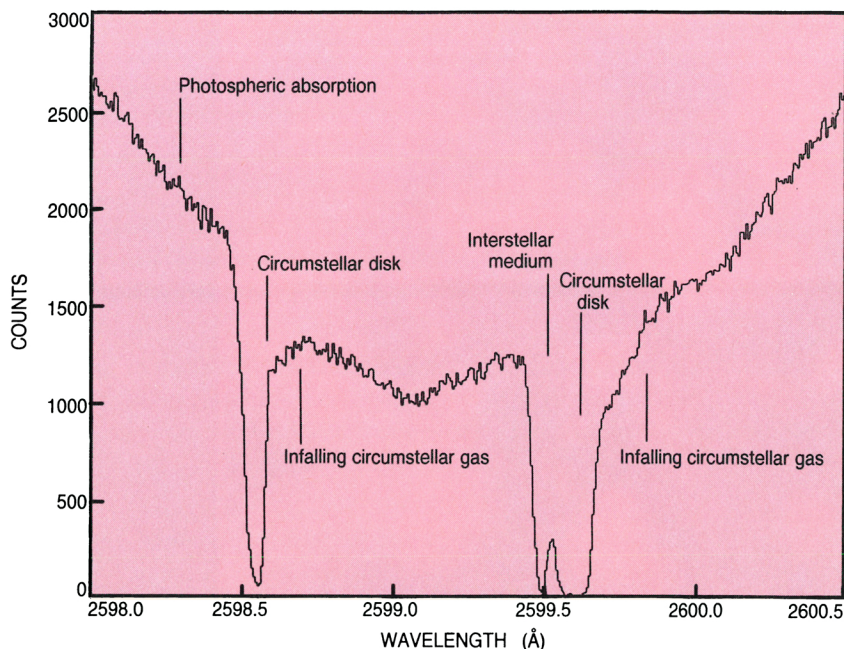
The survey committee's conclusion that the success of the US space astrophysics program depends upon achieving an appropriate mix of mission sizes is essentially an endorsement of the relevant portions of the 1988-89 Strategic Plan² of NASA's Office of Space Science and Applications, which was designed to achieve balance within disciplines, across disciplines and within projected budgets. The plan and the committee's recommendations call for the completion of missions recommended by the astronomical community for the 1970s and 1980s. The survey committee consciously emphasizes the need to commit additional resources for moderate and small missions, and urges NASA to continue applying the

Ultraviolet spectrum of Beta Pictoris

and its surrounding disk of dust was obtained by the Goddard High Resolution Spectrograph aboard the HST. The spectrum shows narrow Fe^+ absorption from both the circumstellar disk and the intervening interstellar medium superimposed on broad stellar photospheric absorption, widened by the high rotational velocity of the star.

The absorption wings, extending to longer wavelengths from the sharp circumstellar 2598.4- and 2599.4-Å features, indicate that gas is falling toward the star from the disk at velocities of up to 60 km/sec.

(Courtesy of NASA and the Goddard High Resolution Spectrograph science team.) **Figure 2**



lessons learned from the troubled 1980s as it implements the plan.

The survey committee endorses the completion of NASA's Great Observatories program, four large missions (described below) with awesome capabilities that cannot be matched by smaller missions. These large missions provide orders-of-magnitude increases in imaging and spectroscopic sensitivity, which are needed to address problems at the frontiers of our discipline, to make new discoveries and to answer in detail the many questions raised by the smaller, more exploratory missions of the past. Although they are expensive, large missions can be efficient and cost effective when amortized over their long on-orbit lifetimes. Large missions involve many researchers in innovative instrument development, support broad community participation in forefront observations, attract students and capture the public imagination. Large missions permit many small groups to carry out frontier research; for example, the investigators selected for the first year of HST observations come from 200 institutions, and each research group typically has only four members.

At the same time, moderate and small missions add a vital dimension to NASA's space science program. They provide relatively rapid access to space, allow for quick response to scientific and technical developments, stimulate progress in technology and provide leadership opportunities for young instrumentalists. Many of the outstanding astronomical missions of the past were modest in scale. The survey committee recommends that NASA "continue to develop a vigorous program of moderate and small missions of limited complexity and shorter development times, with increased use of expendable launch vehicles." Specifically it calls for more moderate and small "Explorer" class missions (described below) to address a broad range of key scientific problems.

The survey committee and its panels also considered the manner in which NASA programs are implemented. In particular, the committee believes that the most successful and cost-effective projects of any size involve an intimate partnership among researchers in universities, NASA and industry. For large programs this requires active participation and authority at the project level by both NASA and non-NASA scientists. Small programs

require even more direct scientific control as well as a return to missions with limited and well-defined scientific objectives, careful attention to technical readiness and cost and appropriate levels of formal reliability and quality. Most important, once a mission is started, it should be completed in a timely fashion: Development times for even modest-sized satellites have grown intolerably long, causing loss of scientific opportunity and vitality—and adding significantly to total cost.

Completing the Great Observatories

The 1990s will be the decade of the the Great Observatories: the Hubble Space Telescope, the Gamma Ray Observatory (to be launched in 1991), the Advanced X-Ray Astrophysics Facility (scheduled for 1998) and the Space Infrared Telescope Facility. These long-lived missions will give Earthbound astronomers access to much of the electromagnetic spectrum.

The HST's mirror flaw, discovered in the midst of euphoric announcements of a golden age in astronomy, plunged the community into a similarly hyperbolic period of despair. There is no question that the flaw will prevent the HST from forming the highest-resolution images of faint objects until some kind of corrective action is taken. However the HST has already returned scientifically important images of planets, star clusters (see figure 1), the debris from supernova 1987A, galaxy cores and gravitationally lensed quasars. The spectrographs, though hampered by reduced efficiency, will surely still observe targets of great interest, especially in the ultraviolet (see figure 2). High-resolution imaging capability will be restored in 1993, when astronauts install an improved Wide Field/Planetary Camera with corrective optics. NASA is also considering replacement of another instrument with a device called COSTAR during the 1993 rendezvous. COSTAR would position corrective optics over the entrance apertures of the Faint Object Camera and the two spectrographs. Two other replacement instruments are now being designed with corrective optics: the Space Telescope Imaging Spectrograph and the Near-Infrared Camera and Multi-Object Spectrometer. The survey committee considers this advanced scientific instrument program for the HST to be of critical importance

to space astronomy.

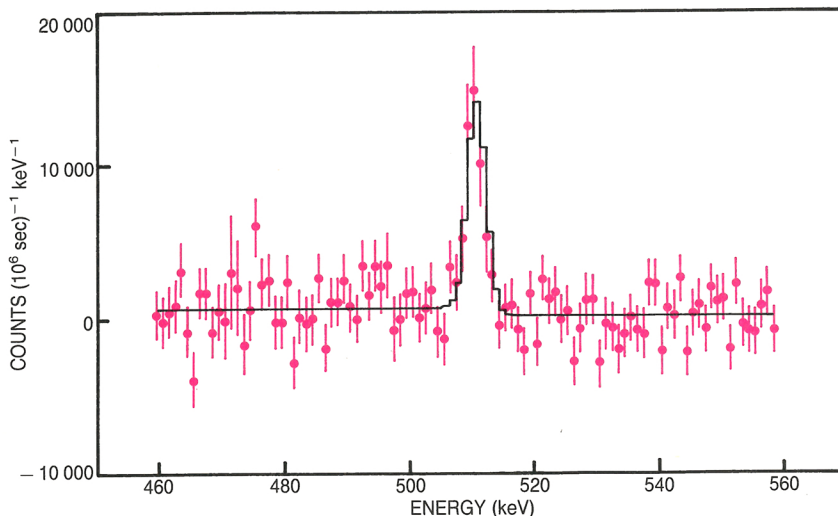
The Gamma Ray Observatory carries four instruments to observe cosmic sources over three decades of energy—from 20 keV to 30 GeV. The GRO's sensitivity and angular resolution (about 5 arcminutes for strong point sources and nearly 1 degree for bursts) are more than an order of magnitude better than those of the gamma-ray missions of the 1970s. The GRO will study explosive phenomena; particle acceleration near neutron stars and black holes; the distribution of cosmic rays and gas in the Galaxy; the intriguing source of 511-keV e^+e^- annihilation radiation near the Galactic center (see figure 3 and *PHYSICS TODAY*, March, page 17); and the energetics of active galactic nuclei and quasars. Although not ideally suited for emission line spectroscopy, the GRO will nevertheless be capable of measuring some of the lines from the direct nucleosynthesis of radioactive elements in supernovae, including the 0.122-MeV line from long-lived ^{57}Co in supernova 1987A.

The Advanced X-Ray Astrophysics Facility is a 1.2-m-diameter, grazing-incidence x-ray telescope that has several instruments capable of subarcsecond imaging and high-resolution spectroscopy in the 0.1–10-keV band. The survey committee "reaffirms the decision of the previous survey,³ *Astronomy and Astrophysics for the 1980s*, that made AXAF the highest-priority large program of that decade, and stresses the importance to all astronomy of deploying AXAF as soon as possible." (Unfortunately, from the time those words were drafted to the time they appeared in print, the AXAF schedule had slipped 11 months for budgetary reasons.) Once in orbit, AXAF will return the US to preeminence in x-ray astronomy (a field that was pioneered by NASA's earliest sounding rockets and satellites) and will have a major impact on nearly all areas of astronomy. For example, AXAF will study the coronas of normal and active stars; perform chemical

analyses of supernova remnants in our own and nearby galaxies; image the active nuclei of galaxies and quasars (see figure 4); resolve the point-source component of the poorly understood cosmic x-ray background; and make fundamental contributions to cosmology. The two-and-a-half-year flight of the Einstein Observatory, AXAF's predecessor, yielded over 1000 published papers covering nearly every branch of astronomy and astrophysics. AXAF's projected lifetime, with servicing, is 15 years.

AXAF measurements of clusters of galaxies illustrate its ability to address fundamental astrophysical questions. A cluster can contain hundreds of galaxies moving through a diffuse, x-ray-emitting plasma, which has a temperature of roughly 10^8 K (see figure 5). Galaxies and gas are gravitationally bound by what appears to be a third, unseen component, the dark matter currently of great interest to cosmologists and particle astrophysicists. Accurate measurements of the quantity and distribution of dark matter would help define its properties and cosmological significance, but obtaining such accurate measurements has proved difficult. Through AXAF's capabilities for both imaging and spectroscopy, it will be possible to determine how the density and temperature of the gas vary throughout the cluster. The equation of equilibrium can then be used to determine the amount of binding mass. Knowledge of the properties of intracluster gas can also be used to predict an apparent shift in the temperature of microwave background radiation that, as it traverses the cluster, is Compton scattered by hot electrons. Comparing this prediction with microwave measurements, one can determine the cluster's distance—and therefore the Hubble constant—independently of all the traditional calibrations of the cosmic distance scale.

Because of AXAF's scale and its superficial resemblance to the HST (both are 30-foot-long cylinders containing telescopes and detectors), it is reasonable to worry



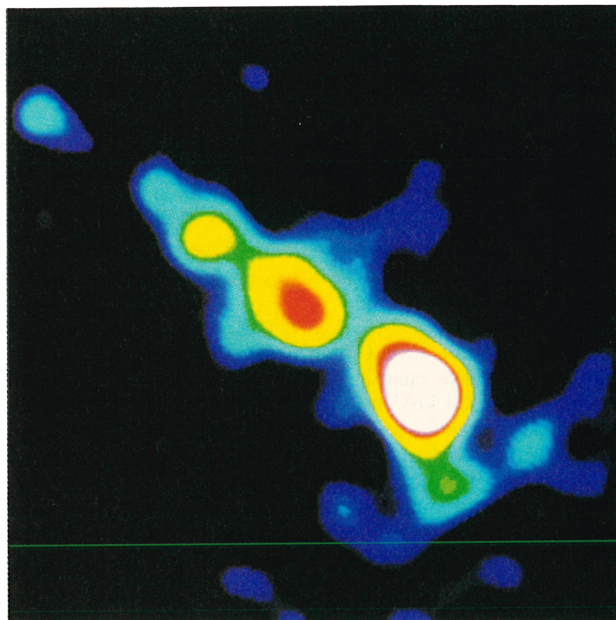
Electron-positron annihilation line at 511 keV was observed from the direction of the Galactic center by a balloon-borne spectrometer flown over Australia in October 1988. The observed radiation is thought to be the superposition of an interstellar component, in which the positrons result from radioactive nuclei synthesized in supernovae, and a compact-source component, in which the positrons result from photon-photon collisions in the accretion disk of a black hole or neutron star in a binary system located near the Galactic center. (Adapted from N. Gehrels, S. Barthelmy, B. Teegarden, J. Tueller, M. Levinthal, C. McCallum, submitted to *Astrophys. J. Lett.*) **Figure 3**

about a repetition of HST troubles. In fact, the programs are quite different. AXAF has a strong technical and scientific heritage from previous x-ray missions; in many ways it is a scaled-up version of the successful Einstein Observatory, launched more than a decade ago. In addition, AXAF is being built under a single prime contractor and managed by a single NASA center with project supervision by experienced NASA and non-NASA scientists. All of these factors and scheduled end-to-end testing mean that AXAF should avoid the kinds of problems experienced in the HST program. NASA's Allen Committee,⁴ which reviewed the causes of the flaw in HST's mirror (see *PHYSICS TODAY*, November 1990, page 19), also examined the quality-control and fabrication processes of the AXAF mirrors at Hughes Danbury Optical Systems. They affirmed that the AXAF mirror program does not suffer from the problems of the HST. However, NASA and the scientific community have to continue working very hard to assure that AXAF avoids the protracted launch delays and associated cost increases of the past decade.

The completion of the Great Observatories is a realistic goal for the 1990s. The survey committee felt it was premature to make a specific recommendation for follow-on missions of similar scale, but called for suitable technology development (discussed below) leading to selection of one of several possible bold new missions by the end of the century.

Accelerating the Explorer program

The Explorer program of special-purpose moderate and small satellites has been at the core of NASA's space science program since its earliest days. Astronomy and astrophysics Explorers have established an outstanding record of scientific achievement at relatively low cost, infusing astronomy and astrophysics with a rich variety of scientific discoveries. For example, Uhuru (SAS-1) performed the first survey of the x-ray sky, discovering binary x-ray pulsars, black hole candidates and pervasive hot gas in galaxy clusters. The Infrared Astronomical Satellite imaged the sky in the infrared for the first time, increasing the number of known infrared sources one hundredfold and finding disks of solid matter orbiting nearby stars and ultraluminous galaxies emitting 99% of their energy in the ir. After 13 years of successful operation the International Ultraviolet Explorer continues to make discoveries in nearly all topics of modern astrophysics, including physical processes in active galaxy nuclei, hot gaseous galaxy halos, massive winds from all kinds of stars and loops of magnetically confined gas protruding from stellar surfaces. Most recently COBE produced a truly remarkable spectrum of the 2.7-K background radiation from the early universe that will probably represent one of the cornerstones of observational cosmology for many decades to come (see *PHYSICS*



Active nucleus of radio galaxy Centaurus A is shown in an x-ray image obtained by the Einstein Observatory. The false color indicates roughly 0.53-keV intensity. The bright source on the lower right is the nucleus itself, thought to be an accreting black hole with mass of about $10^8 M_\odot$. The extension to the upper left is a "jet," which also emits radio and optical radiation and extends roughly 5000 light-years. It is thought that the jet emits synchrotron radiation from ultrarelativistic electrons that are accelerated locally. AXAF will obtain an image 10 times sharper than this one and will also provide detailed spectra. (E. Schreier, C. Jones-Forman and the Smithsonian Astrophysical Observatory.) **Figure 4**

TODAY, March 1990, page 17).

During the 1980s the Explorer program was stymied by economic inflation, rising mission complexity and the program's nearly total dependence on the space shuttle as a launch vehicle. Shuttle delays and the need to redesign missions for Delta launches following the Challenger disaster further strained the Explorer budget. The program has not yet fully recovered—missions originally conceived in the mid-1970s are still waiting for launch. With the time between initial concept and launch approaching 20 years for moderate-sized missions, it is clear that to return it to its former glory, the Explorer program is in need of change. This revival requires both increased budgets and increased productivity within those budgets.

The Explorer program is a "level-of-effort" line-item in the NASA budget; in other words, programs selected by peer review are executed at whatever rate the budget allows. The queue for astronomy and astrophysics missions currently includes the five missions listed in the table at right. The program also supports a number of international cooperative ventures.

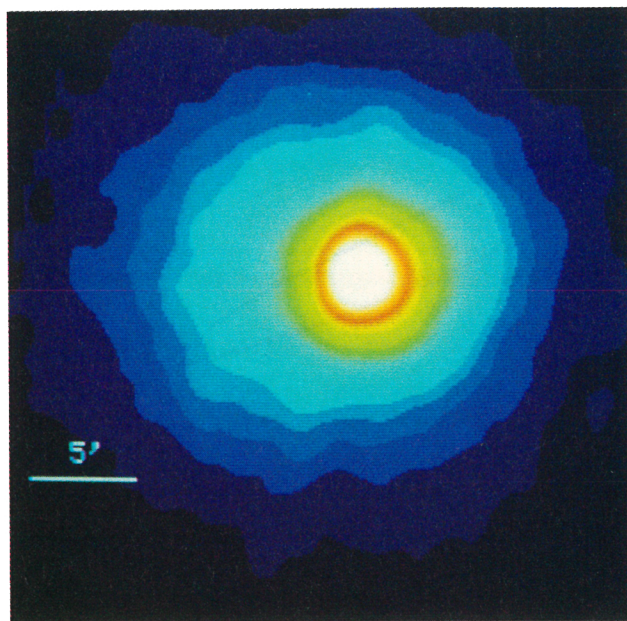
The Extreme Ultraviolet Explorer will survey the sky in several bands between 70 and 760 Å. Subsequent spectroscopic observations with a resolving power ($\lambda/\Delta\lambda$)

of 250 will be carried out through a guest-observer program. EUVE objectives include increased understanding of hot, white dwarf stars and cataclysmic variable stars—close binary-star pairs in which a normal star loses mass to its white-dwarf companion with a violent liberation of energy. The mission will also probe the hot plasmas associated with stellar coronas and the distribution of gas in the local interstellar medium.

The X-Ray Timing Explorer will make spectroscopic and photometric observations in the 1–100-keV range with excellent sensitivity and microsecond time resolution. The XTE will advance our understanding of the physics of accretion flows around neutron stars and black holes, the internal structure of neutron stars and relativistic plasmas in the nuclei of active galaxies. For neutron stars the XTE will obtain new information on orbits, masses, variation in spin rates of accreting pulsars, quasi-periodic oscillations and x-ray bursts from unstable thermonuclear burning.

The Advanced Composition Explorer will measure the elemental, isotopic and charge-state composition of cosmic rays with energies per nucleon from 0.5 keV to 0.5 GeV. The observations should establish the time between nucleosynthesis and acceleration based on the abundances of primary electron-capture nuclides such as ^{57}Co , and should provide new insights about those processes responsible for the synthesis and acceleration of cosmic rays.

The Far-Ultraviolet Spectroscopic Explorer will make spectroscopic observations at wavelengths shorter than 1200 Å with unprecedented sensitivity, bridging the spectral gap between the HST and AXAF. This program will open a window on the cosmos in a spectral region containing fundamental resonance transitions of atomic and molecular species that can be used to probe physical processes in the full range of astrophysical objects and



X-ray emitting gas in the central region of the Perseus cluster of galaxies is revealed in this Einstein Observatory image. At a distance of about 300 million light-years, Perseus is the brightest and one of the most luminous clusters in the x-ray band. Altogether, it contains 3×10^{14} solar masses of gas at a temperature of roughly 10^8 K trapped in the gravitational potential of the cluster, which results largely from dark matter. AXAF measurements will ultimately yield the cluster mass. The scale indicates 5 arcminutes, corresponding to 400 000 light-years. (Courtesy of C. Jones-Forman and the Smithsonian Astrophysical Observatory.) **Figure 5**

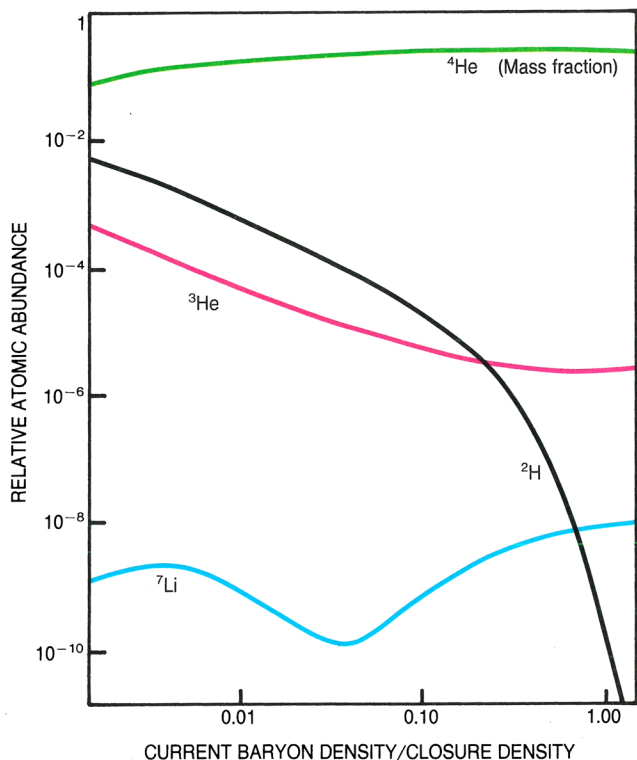
environments, including the early universe. The window also covers the red-shifted absorption of the 304-Å resonance line of ionized helium, which carries information about the evolution of the intergalactic medium.

FUSE will provide unique information about the light-element abundances created during the first three minutes of the universe. In the standard Big Bang model for a homogeneous universe, the abundances of ^2D , ^3He , ^4He and ^7Li relative to ^1H constrain the baryon density during nucleosynthesis, which in turn can be extrapolated to the present density (see figure 6). Nuclear fusion in stars converts ^2D to ^3He and synthesizes other light elements. Thus to measure the primordial value of D/H, one must correct for stellar nucleosynthesis following the Big Bang. This can be done by studying the variations in D/H in astrophysical sites with different degrees of stellar nucleosynthetic processing. The degree of stellar processing can be determined by obtaining measures of O/H and N/H in the same regions being probed for D/H. Extrapolation back to zero stellar enrichment would then provide the primordial value of D/H. This ambitious project will be possible from FUSE far-uv measurements of the Lyman resonance absorption line series of ^2D and ^1H . The absorption lines for the two isotopes are separated in wavelength because of their different nuclear masses, and accurate abundance ratios can be obtained provided a number of lines in the Lyman series of each isotope is

Currently funded Explorer-class satellites

Program	Planned launch date*
Medium Explorers (Delta or shuttle launched)	
Extreme Ultraviolet Explorer (EUVE)	1992
X-Ray Timing Explorer (XTE)	1996
Advanced Composition Explorer (ACE)	1997
Far-UV Spectroscopic Explorer (Lyman-FUSE)	1999
Small Explorers (Scout launched)	
Submillimeter Wave Astronomy Satellite (SWAS)	1995

*Launch dates for missions after 1995 are uncertain.



Fractional abundances of various important light isotopes are shown as a function of current baryon density in the standard Big Bang model of nucleosynthesis. (^4H abundances are plotted as mass fraction rather than relative atomic abundance.) Measures of the crucial ratio of deuterium to hydrogen in a variety of Galactic and extra-Galactic environments will be obtained by the Far-Ultraviolet Spectroscopic Explorer satellite observing in the rich spectral region 912–1250 Å. Accurate measurements of the nucleosynthetic products of the Big Bang are fundamental to observational cosmology. (Adapted from P. Peebles, D. Schramm, E. Turner, R. Kron, submitted to *Nature*.) **Figure 6**

measured. Direct measurements of the nucleosynthetic products of the Big Bang rival measures of the Hubble constant and the cosmic background radiation in importance to observational cosmology.

The EUVE and its Explorer platform spacecraft will be placed into orbit by a Delta rocket in 1992. According to the current plan, the XTE will be launched by a 1996 shuttle mission, during which astronauts will exchange it for the EUVE on the Explorer platform. A second shuttle flight around 1999 would replace the XTE with Lyman-FUSE. Given the uncertainties of the shuttle schedule, the chance of actually seeing Lyman-FUSE in orbit during the 1990s appears remote if NASA follows this plan.

Quick is beautiful: Small Explorer program

In the late 1980s, NASA initiated the Small Explorer program to provide rapid access to space for payloads weighing less than about 200 kg. Astronomy instruments often require pointing systems that weigh almost this much. However, a NASA solicitation provoked a number of imaginative proposals. From these, reviewers selected the Submillimeter Wave Astronomy Satellite, which will explore the Galaxy through the spectral lines of H_2O and

O_2 . While the SMEX program has been greeted enthusiastically by the space science community, there is still concern that its “quick-is-beautiful” objective may be thwarted by increasing technical and management complexity and cost. NASA and the investigators must be determined to see that this does not happen.

To revitalize space astronomy NASA must launch the Explorer satellites currently in the queue, provide for new experiment opportunities and try to restore the high productivity of this essential program. The survey committee makes the following specific recommendations:

Build a dedicated FUSE spacecraft. The committee recommends that NASA augment the Explorer program sufficiently to convert FUSE into a Delta-launched experiment that uses its own dedicated spacecraft. The survey committee believes that a strong coupling of Explorer missions to the manned space program will lead to unnecessary delays and expense. A dedicated Delta-launched spacecraft for FUSE would also increase its on-orbit lifetime and provide an optimized orbit that would improve the operational efficiency of the mission.

Accelerate Delta-class missions. The committee recommends that NASA increase the rate of Explorer missions for astronomy and astrophysics to six Delta-class missions per decade. The missions themselves should be selected by peer review, with adequate attention paid to technical readiness and cost effectiveness as well as scientific merit. Several panels of the survey committee recommend relevant programs of high scientific importance, including high-resolution gamma-ray spectroscopy to study spectral lines from nucleosynthetic processes within our own and other galaxies; submillimeter spectroscopy to survey the rich atomic and molecular spectra of star-forming regions and galaxies; and hard-x-ray imaging to study a variety of Galactic and extra-Galactic sources with 60-arcsecond spatial resolution in the 10–250-keV energy range.

Encourage international collaborations. The ability to place US instruments on foreign spacecraft is a cost-effective way to provide exciting science opportunities while furthering NASA’s mission of fostering international scientific collaboration. NASA has often taken support for such experiments out of the already strained Explorer budget. A budget line for international collaborations will allow NASA to undertake more of these advantageous joint ventures. The survey committee’s report mentions US participation in a German orbiting planetary telescope and very-long-baseline interferometry experiments being conducted with the Soviet Union and Japan (see the article by Charles Beichman and Stephen Ridgway on page 48).

Accelerate the Small Explorer program. The committee recommends that NASA increase the rate of Small Explorer missions for astronomy and astrophysics to five per decade. These should be executed as quickly and as simply as possible and should be selected by peer review. The scientific potential of the SMEX program can be substantially increased by inexpensive, more powerful launchers, such as the advanced Scout or Pegasus rockets.

The survey committee also recommends starting the moderate-sized Astrometric Interferometry Mission (also described in the article by Beichman and Ridgway on page 48).

Training new scientists: suborbital program

Part of NASA’s suborbital program involves placing instruments on sounding rockets, airplanes and balloons to explore new scientific ideas and develop new technologies. This undertaking is the only space science hardware

program that operates on the time scale of a graduate student's academic career, allowing the student to experience all of its aspects, from the development of the instrument to the analysis and publication of the data. The survey committee feels that the program is essential and should be continued.

The suborbital program has an impressive record of scientific accomplishment: for example, the discovery of interstellar molecular hydrogen, the discovery of celestial x-ray sources, the measurement of gamma rays from SN1987A and the Galaxy (see figure 3) and the detection of the rings around Uranus. However perhaps the most impressive accomplishment of the program has been the training of several generations of space instrumentation scientists.

In the ir region the Kuiper Airborne Observatory, a 0.9-m telescope on a C-141 airplane, has been the mainstay of the suborbital program. The survey committee's recommendation to replace the Kuiper Observatory with the Stratospheric Observatory for Infrared Astronomy (known as SOFIA), a new, more capable facility is discussed in the article by James Houck and Fred Gillett on page 32. Other regions of the spectrum can only be studied by higher-altitude balloons and sounding rockets.

Data analysis, theory and experiment

The data flowing from large and small space astronomy missions represent a national treasure. Mining that treasure requires adequate funding for the research scientists who analyze and interpret the data, both from ongoing missions and from earlier missions. The survey committee applauds NASA for recognizing the importance of this activity and for establishing a strong program in astrophysical data analysis and archival research, and it urges that the program be continued at a vigorous level, which should grow in approximate proportion to NASA's support for the analysis and interpretation of observational data (see the article on theory by Christopher McKee and William Press on page 69).

The quality of data from space missions is often so high that the major uncertainty in using those data to infer physical information about the emitting cosmic source is our lack of knowledge about the basic properties of matter. The required transition frequencies, transition probabilities, photoionization cross sections and particle collision cross sections must come from either laboratory measures or theoretical calculations. The survey committee supports a program of laboratory astrophysics aimed at supporting the interpretation of data flowing from moderate and major missions in space astronomy and astrophysics.

Technology for the next century

Technology development carried out during the 1990s will determine the science that can be done in space during the early 21st century. Early attention is particularly important for space applications, for which additional time is required to achieve acceptable reliability through extensive testing.

The survey committee recommends that space technology study and development occur in: optical and infrared interferometry in space; large space telescope technology; submillimeter receiver and telescope technology; and mirror and detector technology for high-energy astrophysics. Specific examples of technology areas deserving attention are high-performance, lightweight and active optics; lightweight and active telescope support structures; novel approaches to x-ray optics; object tracking and pointing; passive and active cooling of telescopes; a wide variety of detector technology; optical surface and

coating technology; low-thrust station-keeping and altitude-control propulsion systems for interferometry; and the development of stable space-qualified lasers for alignment of the elements of an interferometer. Many other examples of technology requiring study and development are discussed in the separate panel reports of the survey committee.

Technology studies should be a prerequisite for starting definition studies for the next generation of space astronomy missions in the second half of the 1990s. A mission to follow the Great Observatories should be selected by the turn of the century once its technology is well understood. It is already possible to identify exciting candidates with strong scientific justifications, such as a large space telescope with a lightweight, 6-m-diameter mirror that would combine the light-gathering power of the largest ground-based telescopes with the excellent image quality, uv sensitivity and millionfold decrease in ir background that are achievable in space; a submillimeter observatory consisting of a deployable 10-m telescope; an array of small optical telescopes operating as an interferometer; an array of orbiting radio telescopes; and a large x-ray telescope of lightweight mirrors equipped with next-generation detectors for imaging and spectroscopy with very high sensitivity.

A major space exploration initiative could return humans to the Moon in the early part of the next century. The survey committee concludes that a cost-effective and scientifically productive astronomical program on the Moon would require early technology development, including pilot programs with substantial scientific return. The chief advantage of the Moon as a site for space astronomy is that it provides a large, solid foundation on which to build widely separated structures such as interferometers. The survey committee recommends that an appropriate fraction of the funding for a lunar initiative be devoted to fundamental scientific projects of wide appeal, supporting scientific missions as they progress from small ground-based instruments to modest orbital experiments to facilities on the Moon.

A reason for optimism

The space astronomy program has survived its most difficult decade. Several recent disappointments remind us that much hard work is still needed to correct all the deficiencies of the past, especially in the prevailing climate of fiscal restraint. However, there is also much that is right about space astronomy, as evidenced by its extraordinary contributions to our understanding of the universe and by the number and quality of missions recently launched and presently under development. The survey committee's recommendations are a sensible program for building on these strengths and revitalizing space astronomy and astrophysics. A large community of dedicated individuals, both in and out of NASA, are devoting their careers to this end. Their motivation is easily found in the spectacular scientific successes achieved in the past and promised for the future.

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