EXPLORING THE UNIVERSE:

SPACE-BASED ASTRONOMY AND ASTROPHYSICS

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Astronomy before 1958[1]

For millennia until the Second World War, astronomical observations were limited to visible light, the type of electromagnetic radiation sensed by the human eye.[2] When people look at the sky with the naked eye, they see only stars and patches of dark against dense star backgrounds, as in the southern Milky Way. With a telescope, one can see nebulae, or clouds of gas, shining either by fluorescence or by reflected light. Large collections of stars that form distant galaxies much like the Milky Way galaxy can also be seen through telescopes.[3]

Although it was known for several centuries that some stars vary in brightness, only a few such stars were known. It was not until 1718 that the English astronomer Edmund Halley noticed that three bright stars had changed their positions in the two millennia since they had been cataloged by Ptolemy, thus recognizing the tiny motions (the proper motions) of stars across the sky. Only with the use of spectroscopy in the

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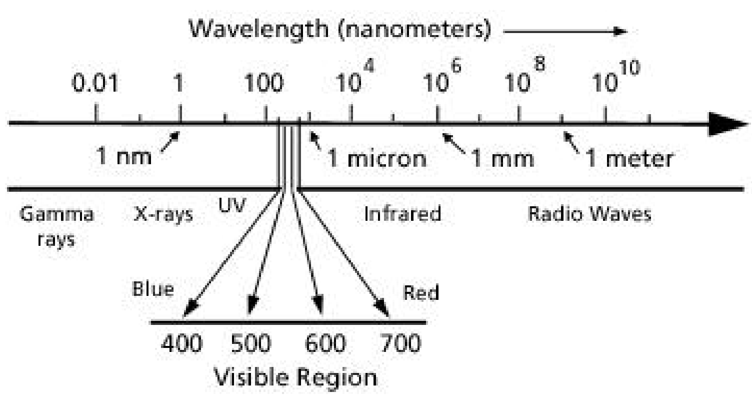
[1] In this essay, astronomical observations are defined as those focused on objects and phenomena existing beyond the solar system. The disciplines of astronomy and astrophysics as considered here deal only with such objects and phenomena. A short section on general relativity is also included.

[2] Astronomers call light and similar radiation "electromagnetic radiation." They describe particular portions of this electromagnetic radiation by wavelength, which increases toward the red, and by frequency and energy, which increases toward the blue. The "rainbow" formed by the spread of the colors is called the spectrum. Wavelength and frequency consider electromagnetic radiation as a wave. The wavelength is the distance between the same portion of the successive cycles; frequency is the number of passages in one second of the same portion of the successive cycles past the same point. Thus frequency is the velocity of the radiation divided by the wavelength. The wave number, a unit frequently used in the infrared, is the inverse of the wavelength in centimeters. Energy measurements consider the radiation as a stream of particles. The energy is proportional to the frequency.

[3] Three galaxies are visible to the naked eye from dark viewing points: the Andromeda galaxy, a close relative of the Milky Way galaxy, and the two Magellanic Clouds, smaller systems that are much nearer to the Milky Way. The latter are visible only from the Southern Hemisphere.

early twentieth century could astronomers measure the motion of stars toward and away from the Earth (the radial velocities). In 1939, physicist Hans Bethe proposed that the light observed from most stars results from the conversion of hydrogen into helium in the stellar cores and delineated a probable chain of reactions to accomplish this conversion.[4] As helium is slightly lighter than four hydrogen atoms, this reaction changes a bit of matter into energy. Therefore, most stars are changing with time, but this change is so slow that the sun has remained essentially unchanged for about five billion years and will remain nearly the same for another five billion years. The heavens were considered the epitome of calm and lack of change. Observations in other wavelengths were to show how misleading the observations in the visible region had been.

In the 1930s, astronomer Karl Jansky first detected radio emission from the center of the Milky Way.[5] The first attempt to study celestial objects in wavelengths other than the visible was made as the result of the development of radar in the 1940s. Grote Reber,



Electromagnetic Spectrum

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[4] Hans Bethe, "Energy Production in Stars," *Physical Review* 55 (1939): 434-56.
[5] Karl Jansky, "Electrical Disturbances Apparently of Extraterrestrial Origin," *Proceedings of the Institute of Radio Engineers* 21 (1933): 1387-98.

an amateur astronomer, observed strong emission from the constellation Sagittarius and weaker maxima in the constellations Cygnus, Cassiopeia, Canis Major, and Puppis.[6] These emissions at long wavelengths were puzzling. They did not show the variation of intensity with wavelength that would be expected for a thermal source. Eventually, I. S. Skhlovsky realized that some continuum radiation (that is, radiation not restricted to a narrow region of the spectrum), such as that from the Crab Nebula, resulted from electrons moving with nearly the speed of light in a strong magnetic field.[7] Other radio emission appeared to come from regions in which particles slammed at high speed into material already present. Also during the 1940s, Hendrik van de Hulst, a young Dutch astronomer, recognized that neutral hydrogen had a very weak transition that radiated and absorbed in a narrow portion of the observable radio region.[8] In spite of the weakness of the transition, scientists soon observed a great abundance of hydrogen between the stars.[9] More recently, astronomers have detected many molecules in the radio region of the spectrum.

Since the invention of the telescope, astronomers have been frustrated by the multiple problems presented by Earth's atmosphere. First and foremost, the continual density fluctuations in the atmosphere have blurred astronomical images, preventing, until recently, even the largest telescope from observing details on planetary surfaces or in dense star fields any finer than those that can be seen easily with a good amateur telescope. Second, and almost as important, the constituents of the atmosphere block

[6] Grote Reber, "Cosmic Static," *Astrophysical Journal* 100 (1944): 279-87.
[7] I. S. Skhlovsky, "On the Nature of the Radiation from the Crab Nebula," *Doklady. Akademii. Nauk SSSR* 90 (1983): 983-86.
[8] Hendrik Christoffel van de Hulst, "Radio Waves from Space" (in Dutch), *Nederlandische Tijdschrift Natuurkunde* 11 (1945): 201, 210.
[9] H. I. Ewen and E. M. Purcell, "Radiation from the Galactic Hydrogen at 1420 Mc/Sec," *Nature* 168 (1951): 356.

most of the electromagnetic spectrum, and electrons in the ionosphere block access from the ground to long-wave radio waves. Although the latter makes long distance radio reception possible, it also cuts out an important region of the astronomical spectrum. The atmosphere also scatters light, making it impossible to see a faint star near a bright one. Finally, the atoms and molecules in the atmosphere emit light, ensuring that the sky as seen from the surface of the Earth is never completely dark .

For these reasons, some astronomers became interested in the possibility of observations from above the atmosphere.[10] In 1946, Princeton University astronomer Lyman Spitzer wrote a short paper in which he explained the advantages of a space-based telescope; the origins of planning for the Hubble Space Telescope can be traced to this paper.[11] [III-1] In 1952, Fred Whipple, a Harvard astronomer, discussed briefly some of the technical aspects of an ultraviolet (UV) telescope in space. He assumed that it would be operated in conjunction with a human-occupied space station, but not attached to the station.[12]

Astronomers soon had an opportunity to make observations from above the disturbing atmosphere. At the end of World War II, the United States had captured a number of German V-2 rockets and the Army was anxious to test them. The military solicited scientific experiments to serve as functioning payloads for these tests. (See Chapter 1 of this volume for more information on these experiments.) The first celestial photograph taken from a scientific payload flown on a V-2 was a spectrum of the sun,

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[10] Others, however, were skeptical of the usefulness of observing the heavens from space. See the section later in this chapter on the Great Observatories for more information on this subject.
[11] Lyman Spitzer, *Astronomical Advantages of an Extra-Terrestrial Observatory* (Santa Monica, CA: Project RAND, 1946). For additional background on Spitzer's vision of a space telescope, see Lyman Spitzer and Jeremiah P. Ostriker, eds., *Dreams, Stars, and Electrons* (Princeton, NJ: Princeton University Press, 1996).

obtained by Richard Tousey and his colleagues at the Naval Research Laboratory (NRL) in 1946.[13] Researchers from around the country flew a variety of instruments aimed at answering questions in solar and atmospheric physics. In the early 1950s, astronomer Jesse Greenstein, then at the University of Chicago, built a spectrograph for stellar observations. The rocket on which the experiment rode failed, as many others did in these early years.[14] In November 1955, researchers in the Rocket Branch at NRL succeeded in flying the first UV stellar photometers.[15] Since hot stars emitted much of their radiation in the UV that was not accessible from the ground, it made sense that the first astronomical observations of the night sky were directed to observations of this region; the earliest results, with very low angular resolution, proved to be unreliable. By then, the smaller, more reliable Aerobee rocket had replaced the V-2, and became the launch vehicle that dominated the sounding rocket astronomy program for several decades.[16]

NASA Starts an Astronomy Program

When it began operations in October 1958, NASA was composed primarily of two groups of people: those who had been part of the National Advisory Committee for

[12] Fred L. Whipple, Lecture at Second Symposium on Space Travel at the Hayden Planetarium, American Museum of Natural History, New York, NY, 1952.

[13] W. A. Baum, F. S. Johnson, J. J. Oberly, et al., "Solar Ultraviolet Spectrum to 88 Kilometers," *Physical Review* 70 (November 1946): 781-82.

[14] After his experiment's failure, Greenstein promised to have nothing more to do with trying to conduct experiments in space. Although he was never responsible for another instrument, and at first was very negative toward the space program, he remained interested in the possibilities of observing the ultraviolet spectra of stars and served as both a formal and informal advisor to the NASA astronomy program.

[15] Byram et al., in *The Threshold of Space*, M. Zelikoff, ed., (London, England: Pergamon Press, 1957).

[16] For more information, see David H. DeVorkin, *Science with a Vengeance: How the Military Created the U.S. Space Sciences after World War II* (New York, NY: Springer-Verlag, 1993).

Aeronautics (NACA) and a large contingent from the NRL. The latter included most of the NRL Rocket Branch and of those working on Project Vanguard at NRL.

The first astronomical activity in NASA was the continuation of the sounding rocket program already underway at NRL. James Kupperian, formerly of NRL, led a group at NASA's Goddard Space Flight Center (originally the Beltsville Space Center) that also included several others from the NRL rocket program. At the same time, some astronomers remained at NRL, including Herbert Friedman, who continued to lead a strong program there, particularly in X-ray astronomy.

Although astronomers originally wanted to explore the entire spectrum not accessible from the ground, many astronomers were particularly interested in the UV region. Molecular ozone restricts ground-based observations to the near UV.[17] Although both X-rays and UV emission had been observed from the sun years before the start of NASA, instruments launched on sounding rockets had observed other objects only in the UV. Hence, the early sounding rocket program in NASA concentrated on the UV.

Gerhardt Schilling, who had been an assistant to astronomer Fred Whipple at the Smithsonian Astrophysical Observatory (SAO), joined NASA as head of the astronomy program. John O'Keefe, who had recently joined the Theoretical Division at Goddard, assisted Schilling on a part-time basis. The first job of Schilling and O'Keefe was to start the development of several experiments and spacecraft that would become part of NASA's first astronomy satellites, known as the Orbiting Astronomical Observatories (OAOs). [III-4]

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[17] Specifically, it restricts ground-based observations to wavelengths longer than 300 nanometers. A nanometer is 1×10^{-9} meter.

In February 1959, the author of this essay joined NASA from the Radio Astronomy Branch at NRL to become Head of the Optical Astronomy Program, which included the UV. Schilling left less than a year later, and the author took over the entire astronomy program. At that time, the program included not only all wavelengths from high-energy gamma rays to long-wave radio waves for all celestial objects observed from the vicinity of the Earth, but also geodesy.[18]

A primary activity in the first few years was alerting the astronomical community to the opportunities offered by the NASA program and, at the same time, learning what possibilities were of interest to various astronomers. [III-3] The latter, somewhat modified by the author's understanding of both astronomical questions and technical capabilities, was the basis of the planned program. Astronomers, practitioners of a very old science, deal with long-lived objects and thus tend to be conservative. Hence, it is not surprising that there were social as well as technical problems to be met in the development of the new NASA astronomy program.

Technical and Social Challenges of a NASA-Supported, Space-Based Astronomy Program

- *Technical Challenges*

The early attempts to observe the sky in the ultraviolet used spinning rockets. Astronomical objects beyond the solar system, however, are faint, and except for studies of the very brightest objects, relatively long observations of a single target are required.

[18] NASA's attempts to establish a geodetic satellite program were strongly opposed by the Air Force and traversed a rocky road until the program was finally established a few years later.

Obtaining lengthy observations with the spinning rockets proved impossible because of the short exposure time for each part of the sky.

The development of satisfactory pointing controls was essential both for payloads on sounding rockets and for satellites. NASA's first orbiting missions designed to study the sun, the Orbiting Solar Observatories (OSOs), were able to provide reasonable three-axis pointing in a particular direction by locking onto the sun, but could not point to any other region of the sky. The first satellite to provide versatile three-axis pointing was the first of NASA's major astronomy missions, Orbiting Astronomical Observatory (OAO)-1.[19] The OAOs provided a breakthrough with even slightly better pointing than the sounding rockets of that era.[20] The fine detail in astronomical sources requires good imaging. Astronomers also want to observe a long stretch of a spectrum at the same time. Hence from its astronomy program's inception, NASA has constantly needed to develop sensitive imaging detectors. In the 1960s, ground-based astronomers used photographic plates for the visible regions, but this procedure was too complex and expensive for astronomical observations from satellites.[21] Photographic film was used successfully in rockets, but film sensitive to the UV tended to scratch easily and was difficult to handle. Early on, researchers also used proportional counters, UV versions of Geiger counters, and various similar electronic detectors for the different spectral regions. Astronomers also used the photomultiplier, which had an extensive history in ground-based astronomy.

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[19] The OAO program is discussed further in the section of this essay on optical astronomy.

[20] It is interesting to note that both systems came to fruition in 1965. Both provided pointing accurate and stable to within one arcminute, a distance smaller than the apparent size of a half dollar placed at one end of a football field and viewed from the other. By contrast, the Hubble Space Telescope can point and hold its position to within 0.01 arcseconds. If an airplane taking off from New York could be guided with this accuracy, it could land on a dime in Los Angeles. As small as this distance seems, it is large compared with many details in astronomical objects.

[21] The national security community had used films in photo-intelligence satellites and had recovered them.

Neither the proportional counter nor the photomultiplier had imaging capabilities. On OAO-3, a photomultiplier that measured each point individually was scanned across the spectrum. Intensified vidicons (a space variant of a television camera) were used in several satellites, including OAO-2 and the International Ultraviolet Explorer (IUE), but these were difficult to calibrate, had a distorted field, and were not particularly sensitive. By 1980, solid state detectors called digicons became available for one-dimensional imaging; they are still used for low-resolution spectra. Vidicons were finally replaced by charge-coupled devices(CCDs), which were developed by the national security community and, in the 1970s, for television.[22] The first one used in a satellite was flown in the Wide Field Planetary Camera on the Hubble Space Telescope (HST) to produce most of the familiar pictures from the telescope. CCDs are now being used generally for optical and high-energy space astronomy as well as for ground-based studies.

- *Social Challenges*

Throughout the space astronomy program, NASA has had to address a number of "social" issues. An early challenge was arousing the interest of members of an astronomical community that was comfortable with the instruments they had used for decades. There was a clear division of interest between the astronomers in the West, who had extensive access to large, ground-based telescopes, and those in the East, who lacked such facilities. Astronomers at Princeton, Harvard, and Wisconsin were among those anxious to get involved in the space astronomy program. In contrast, those at the California Institute of Technology and the various campuses of the University of

[22] Although a bare charge-coupled device is sensitive only to the red and near infrared, it can be coated with a phosphor sensitive to other wavelengths or used with another imaging device. Either of these acts as a

California in general thought that the space program was a waste of time and money.[23] Also, many astronomers in 1960 had had relatively little background in developing sophisticated instruments. The influx of observers trained as experimental physicists solved this problem. With the late 1970s availability of the IUE, a satellite telescope became available that could be used much like a ground-based telescope. This mission allowed the majority of academic astronomers to become comfortable with space instruments as a natural addition to their repertoire, a comfort factor that later increased with the HST.[24]

Before World War II, most astronomy in the United States had been supported privately. The major involvement of scientists in the war effort led to substantial government funding of many sciences, including some support of astronomy by the Air Force and by the Office of Naval Research. After the establishment of the National Science Foundation (NSF) in 1950, that agency became the major supporter of American astronomical research. With the founding of NASA, it was obvious that making observations from sounding rockets and satellites was going to include astronomical observations. NSF Director Alan Waterman feared that the space-based research, which was so much more expensive than comparable ground-based astronomy, would overwhelm the latter activity, which still had a strong role to play in astronomical research. In an effort to ensure that both types of astronomy remained viable, Waterman

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wavelength converter for the CCD.

[23] The issue of geographical differences of opinion is discussed further in Robert W. Smith, *The Space Telescope: A Study of NASA, Science, Technology, and Politics* (New York, NY: Cambridge University Press, 1989), pp. 47-48.

[24] IUE and HST are discussed in the Optical Astronomy and Great Observatories sections of this essay, respectively.

and NASA Administrator T. Keith Glennan signed a memorandum of understanding in 1959 agreeing that NSF should be responsible for ground-based astronomy and NASA only for space astronomy. Despite the agreement, the border of responsibilities between the agencies remained fuzzy. Although the division was clear for satellites and rockets, it was less clear for balloon observations. Moreover, NASA flight programs relied strongly on ground-based data to understand the space results. The problem was solved by close cooperation and information exchange between the agencies at the program level. [III-9]

NASA's interest meant not only access to new techniques in astronomy and the avoidance of the many problems presented to astronomy from the ground, but also a new source of funding for instrumentation, observations, and theory. Moreover, the interest in space generated by Sputnik and the formation of NASA attracted many new people into astronomy. The membership of the American Astronomical Society, which includes almost all professional astronomers in the United States, tripled between 1960 and 1970.

The creation of an astronomy program operated by NASA also presented scientists with a new approach to managing government-provided funds. The NSF used a hands-off approach, checking only that a scientist was making satisfactory progress in NSF-funded research. Because of the necessity to meet flight schedules and because of the higher cost overrun potential of space efforts, NASA has practiced more detailed management for most of its flight programs and the ground-based efforts on which they depend.[25] Most astronomers were not only unused to such detailed management, but in fact tried to rebel against it. Although astronomers and physicists involved with the design and development of satellites recognized the complexity of the undertaking and the valuable assistance of NASA engineers, submitting to paperwork requirements, scheduling constraints, and constantly changing budget restrictions continued to rankle. Most investigators would also have preferred a freer hand to do things their own way, going to NASA only for needed help.

Throughout the program, university-based astronomers have questioned the competence of the civil service astronomers working for NASA.[26] On the whole, university astronomers felt from the early days of the space agency that NASA was overly bureaucratic and treated astronomers at NASA centers preferentially.[27] Part of the problem was that the astronomical community generally had no appreciation of the complexity of satellite projects. This issue became particularly evident in 1966, when NASA Administrator James Webb asked Harvard professor Norman Ramsey to chair a committee to advise NASA in the execution of a National Space Astronomy Observatory, among other projects.[28] [III-11] The Ramsey Committee's final report suggested that the astronomy program be transferred to a consortium of universities.[29] [III-12] NASA did not accept the suggestion that the astronomy program be run entirely by an outside consortium, but attempted to curb the academic scientists' unhappiness with the degree of their involvement in program planning by establishing an Astronomy Missions Board, made up of external astronomers, that would advise NASA routinely.[30] [III-14, III-15]

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[25] Research not tied to launch deadlines and comparable in cost to that funded by the NSF has been managed in much the same way as most NSF efforts, allowing the investigator substantial freedom with little detailed oversight.

[26] This was somewhat less of a problem in the geophysics discipline, in which the scientists who were later part of NASA had played an active role in the International Geophysical Year.

[27] NASA headquarters made a serious attempt not to give preference to center astronomers but to some extent it was unavoidable, as the lead project scientist was always from a NASA center.

[28] James Webb to Norman Ramsey, January 14, 1966.

[29] NASA Ad Hoc Science Advisory Committee, "Report to the Administrator," August 15, 1966.

[30] NASA Management Instruction 1156.16, "NASA Astronomy Missions Advisory Board," September 25, 1967; Robert Doyle, ed., *A Long-Range Program in Space Astronomy: Position Paper of the Astronomy Missions Board* (Washington, DC: NASA SP-213, July 1969).

Since then, NASA has routinely received advice on its astronomy and astrophysics programs from both committees of the National Research Council/National Academy of Sciences and from external advisory committees reporting directly to NASA. [III-31, III-33] Although over the years there have been occasional tensions in the relationship between NASA and external scientists, in general the relationship has been mutually productive. [III-35, III-36]

The issue of the position of university astronomers arose again in the decision of where to situate the organization that would manage the selection of scientific observers using HST. In this case, NASA maintained control and oversight of spacecraft operations, but resolved to locate a Space Telescope Science Institute outside of NASA, thus stimulating the anger of astronomers at NASA's Goddard Space Flight Center who had wanted that responsibility. [III-27] In the case of the Chandra X-ray Observatory, launched in 1999, operations were contracted to an academic institution, but the selection of observers still remained with NASA.

Adding to the discomfort of the academic astronomers has been the bureaucracy inherent in a government agency, which must assure Congress and the public that funds are being well spent and, as mentioned above, to meet flight schedules and keep costs under control. A part of the problem is that NASA has operated chiefly as an engineering organization, responsible for the solution of technical—as opposed to scientific—problems, and for the management of complex flight programs.

Scientists and engineers have very different cultures and approaches to problems. The scientist wants to know *why* things happen or have come to be. There are many approaches to the solution of such a question, and usually a number of approaches must be combined to find the answer. Moreover, along the scientist's way, new questions develop, often pursued instead of completing the original quest. The path to solution is rarely direct and sometimes not even in the original direction. In contrast, the engineer wants to know *how* things operate. He or she tries to solve a specific problem, usually under both time and money constraints. While the engineer may experiment with different approaches, he or she must remain on a direct path. Moreover, the final product from an engineer must work properly the first time; both property and lives depend on it. These differences in approach and objective give rise to different ways of looking at problems and cause difficulties when the two groups try to communicate. As a scientist who worked with engineers before joining NASA, the author has often said that in her first year at NASA one of her major jobs was to act as an interpreter between scientists and engineers.

Yet another issue debated by astronomers inside and outside NASA was the extent to which the same basic spacecraft, with minor modifications, should be used for several missions, as opposed to developing an unique satellite for each mission. The result has been a compromise. The OSOs, the OAOs, the Small Astronomical Satellites (SASs), and the High Energy Astronomical Observatories (HEAOs) used the same basic design for each member of the series, but allowed for improvements and modifications to suit each mission. This tactic was generally effective for the early period in which failures were not uncommon, money was plentiful, and the time between launches was brief. Nevertheless, mission-to-mission modifications increased costs, and thus it has never been clear whether individual spacecraft or a series of similar spacecraft have been more cost effective. In contrast, the Great Observatories have each been individually designed, as was the IUE, although the latter was based to some extent on the SAS design. The Extreme Ultraviolet Explorer (EUVE) was to be the first of a series of Explorers using a planned standardized platform, but so far it is the only one to have used that platform.

An additional issue with which astronomers have had to deal since the NASA space astronomy program's inception has been the question of access to the results of observations. In the beginning, the individual investigators responsible for each instrument tended to consider the data proprietary. Moreover, early instrumentation was sufficiently difficult to use that the data were hard to interpret by anyone not intimately involved in the design. Yet, restrictions on use of the data were inconsistent with the fact that the data were paid for by the American public and hence were public property. Gradually, NASA developed a policy that gave individual investigators priority in the use of their mission's data for a finite period of time, often one year. After this time, the investigator would be responsible for depositing the data promptly in the NASA Space Science Data Center in a generally usable form together with full documentation. Although it took many years for some of the early data to be deposited, this responsibility has been well recognized, and scientists are submitting the data to the Center more quickly now. This data archive has been the source for numerous scientific papers, often in areas not envisioned by the original instrument designers.[31]

[31] Modern software now makes it possible to find what observations have been made of an object or region of the sky by any space instrument, and then to request the appropriate data electronically. Many sources of

Modern satellite instruments are frequently general-purpose systems. Astronomers not on the development team are often anxious to address different scientific questions than those initially proposed. As space astronomy has become more routine and instruments have been designed that are easier to use, it has become the custom to conduct a guest observer program on each major satellite. Thus, the selection of the data to be obtained is no longer restricted to the instrument developers. Although the fraction of time dedicated to the guest observer program varies with the satellite, it usually starts only after a period in which the designers have full use of the instrument. This practice insures that the instrument is working as expected and that its operation is well understood, and it rewards the developers with forefront data in return for the years they have spent on the project. After this period, the guest observer program is normally scheduled for an increasing portion of the time as the satellite ages. The guest observer program requires that the calibration and reduction of observations be standardized and made available quickly by the overseeing institution.

International Cooperation

International cooperation has always been an important component of the NASA astronomy program. Not only do scientists tend to pay less attention to national boundaries than politicians usually do, but also NASA wished to encourage space activity in the major European and other allied countries when the program started. Many cooperative sounding rocket flights have taken place over the years with a variety of

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ground-based data can also be accessed. For the new major observatories, it has become customary to release some data as soon as a reasonable calibration has become possible. For the HST, data are archived quickly in raw form and calibrated "on the fly" when they are requested, although a specified proprietary period may still apply.

countries. While the Department of Defense's Transit satellite made the first low, single frequency radio astronomy measurements, the first such studies in which NASA was involved were made by Alouette I, a satellite designed and built by Canada to study the ionosphere.[32] UK-5, also known as Ariel 5, was designed and built by the United Kingdom and flown in 1974 on a NASA launch vehicle. It carried long-wave radio and X-ray astronomy experiments, including one developed by American astronomers.[33] The same British group involved in this mission had flown a similar X-ray instrument on OAO-3. In another cooperative program, the Netherlands Astronomical Satellite was built by the Dutch, but both the United States and the Netherlands participated in its design, and it carried instrumentation from both countries. The Infrared Astronomical Satellite (IRAS) entailed a similar division of responsibility between the Netherlands and the United States.

NASA also has taken advantage from time to time of an Italian launch facility, San Marco, off the coast of Kenya. Because this site is near the equator, satellites launched from San Marco can reach a sufficiently high altitude to minimize air drag and still stay below the Van Allen radiation belts. The particles in the Van Allen belts not only present problems for satellite electronics but also, perhaps more importantly, confuse many scientific instruments, particularly those designed to measure high-energy radiation. In addition, American astronomers have made use of the Woomera rocket launch site in Australia to launch sounding rockets to observe the southern sky, which cannot be observed by rockets launched from the United States.

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[32] For an interesting account of the early history and development of Alouette, see "Alouette/ISIS: How It All Began," http://www.lark.ieee.ca/library/milestone/keynote.htm.

Both the competition for guest observer time and access to the data from all instruments have always been open to all competent users, whatever their nationality. In addition, NASA has routinely selected the best scientific instruments for flight regardless of the nationality of the proposer. The only restriction is that NASA transfers no funds to a foreign country to support participation in a NASA mission; hence, investigators from other countries must find their own support.

Today, few major astronomy satellite missions are restricted to a single country. Much of the future activity in NASA's X-ray astronomy program is being planned in conjunction with Japan. A particularly successful radio astronomy effort has been the Very-Long Baseline Interferometry Space Observatory Program (VSOP), which was built and launched by the Japanese in 1997 as one component of a worldwide Very-Long Baseline Interferometer (VLBI) network.[34] Astronomers from the Massachusett's Institute of Technology, NASA's Jet Propulsion Laboratory, and the National Radio Astronomy Observatory as well as those from many other countries have participated in ground-based observations in conjunction with this satellite. Together, these measurements of radio sources provided the finest detail obtained in any part of the spectrum. NASA has been an international collaborator on another space telescope to conduct VLBI observations, the Russian RadioAstron mission, which has not yet been launched.[35]

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[33] Memorandum of Understanding between the United Kingdom and the United States National Aeronautics and Space Administration, November 2, 1970.

[34] The VLBI technique links telescopes throughout the world to obtain a resolution equivalent to a telescope more than 11,200 kilometers in diameter. As the angular resolution of a telescope is proportional to the wavelength of the radiation divided by the diameter, this long baseline provides images in the radio region comparable to those possible in the optical with a large single mirror. The VSOP satellite extended this baseline by several times to provide correspondingly better resolution.

[35] Orbiting Very-Long Baseline Interferometry (OVLBI) Science Consulting Group, *Scientific Assessment of U. S. Participation in VSOP and Radioastron*, January 23, 1989.

As satellites have become more complex, extensive efforts have been made to involve other countries in the providing instruments and other spacecraft components. For very expensive missions such as the HST and those currently planned for coming years, sharing the costs among two or more countries makes the mission more affordable for all. Congress in the early 1970s required NASA to cooperate with other nations on what became the HST. Europe provided the solar panels and a high-resolution camera on the spacecraft.[36] [III-29] The European Space Agency (ESA) has included involvement in two predominantly American astronomy missions, the Next Generation Space Telescope (NGST) and the Laser Interferometer Space Antenna (LISA), in its planning for the future.

Relations with the Human Space Program

Within the first few years of NASA's existence, it became clear that human endeavors in space would dominate the agency's agenda. The question of the relation of the space science program—including astronomy—to the human space flight program arose once the Apollo program got underway.[37] {III-13} The earliest planning for the Large Space Telescope (later to become the HST) by the aerospace industry and by NASA's Langley Research Center, which also did early planning for the human flight program, envisaged active observing with a human riding with the instrument and

[36] Memorandum of Understanding between the European Space Agency and the United States National Aeronautics and Space Administration, October 7, 1977.
[37] A number of documents from the 1960s show some of the thinking of the time about human involvement in scientific projects. A document that provides great insight into some of this thinking is G. C. Augason, "Manned Space Astronomy," November 1966.

perhaps looking through the telescope.[38] Astronomers were finally able to convince engineers that this was not practical. Not only did astronomers not normally observe visually through ground-based instruments, but also the human eye is not sensitive to many of the wavelengths to be observed from space. In addition, a human moves and thus would disturb the pointing of the instrument; humans also need the very air-filled environment that astronomers wanted to leave behind through the use of satellites.

During the Apollo program, enthusiasm for human participation was high among those astronomers interested in the space program. In 1965, the National Academy of Sciences' Space Science Board (SSB) conducted a summer study that discussed the possibilities of human maintenance, instrument exchange, and recovery for a space-based telescope.[39] [III-10] Astronomers understood that these functions could be carried out in low-Earth orbit, in geosynchronous orbit, or on the Moon. The question of putting an observatory on the Moon, however, became moot for some time when NASA decided not to return to the moon after the 1972 Apollo 17 mission. The planning for the Hubble Space Telescope took full advantage of these possibilities, at least in low-Earth orbit, and the program execution, which has included several human servicing efforts, has fully substantiated the value of human interactions with robotic facilities.

Various small astronomical experiments were flown on Gemini and Apollo missions. Gemini astronauts photographed the spectra of celestial objects using hand-held cameras. Early human flights provided a way in which instruments could be pointed at individual targets for times longer than sounding rocket flights. Later, during Apollo

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[38] One of the leading studies on such a project was The Boeing Company Aerospace Group, "A System Study of a Manned Orbital Telescope," prepared for NASA Langley Research Center under contract NAS1-3968, (Seattle, WA: D2-84042-1, 1965).

16, astronauts successfully placed on the Moon's surface a far-UV camera and spectrograph developed by a team led by NRL astronomer George Carruthers. [III-16] This instrument provided a large number of photographic spectra, primarily of hot stars.

During the mid-1970s, NASA made a decision to tie its science program tightly to the human space flight program, arguing that the developing Space Shuttle would provide relatively inexpensive, frequent access to space. Because the shuttle needed payloads and because projections were that shuttle launches would cost less than expendable launch vehicle launches, all astronomy missions were planned for the shuttle in that period.[40] [III-19] The *Challenger* accident changed planning precipitously. As a result of the extensive delays after the accident, the slower launch schedule, and the escalating costs of shuttle launches, most scientific missions, including those devoted to astronomy, were dropped from the shuttle manifest.[41] This change caused significant redesign problems for missions well along in planning at the time of the accident, greatly increasing the costs of these missions.

The planning for the shuttle included an extensive study of the features the shuttle would require in order to support scientific experiments and observations.[42] The European Space Research Organization (ESRO) decided in 1973 to provide a facility on the shuttle in which to conduct experiments in a wide variety of scientific disciplines.[43] [III-20] This facility, Spacelab, flew several times, although perhaps not frequently

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[39] Space Science Board, *Space Research: Directions for the Future* (Washington, DC: National Academy of Sciences, 1966).
[40] NASA, *Final Report of the Space Shuttle Payload Planning Working Groups: Astronomy* (Washington: Government Printing Office, May 1973).
[41] A few missions, including the Great Observatories, remained on the shuttle.
[42] A NASA/European Space Research Organization (ESRO) committee made a study of the resources required on the Shuttle for a variety of science experiments.
[43] NASA Astronomy Spacelab Payloads Project, *Interim Report of the Astronomy Spacelab Payloads Study: Executive Volume* (Washington: Government Printing Office, July 1975).

enough to have justified its cost. It was comprised of several components that could be flown together or separately. A pressurized cabin provided facilities to accommodate numerous small experiments that benefited from human interaction or used the crew as experimental subjects. When flown, it occupied only part of the shuttle payload bay. In the additional space in the bay, there were pallets on which experiments could be mounted and facilities to permit crew communication with the instruments on these pallets. This permitted astronaut manipulation of the experiments if desired. Another Spacelab component, an instrument pointing system, could also be flown in the unpressurized portion of the Shuttle bay. This could accommodate several sets of instruments pointing at the same object at the same time. Although this system was particularly suitable for solar observations, it was also used successfully for non-solar observations in the UV and in X-rays.

Spacelab 2, the third Spacelab mission, was flown in 1984, and was primarily dedicated to astronomy. The pointing system carried four solar telescopes, and the payload bay also carried a large, hard X-ray telescope on a pallet and a helium-cooled infrared (IR) telescope on its own mount. The largest experiment in this payload was a 2300-kilogram cosmic-ray detector.

In both 1990 and 1995, Astro flew on the Instrument Pointing System and a Broad Band X-ray Telescope (BBXRT) flew on its own pointing system. Astro included three instruments: a UV photopolarimeter,[44] a UV imaging telescope, and a 90-centimeter telescope feeding a UV spectrometer. Although optimized for the far UV, this spectrometer could be used to provide coverage of portions of the UV and the nearer

[44] A photopolarimeter measures the brightness of an object as a function of the direction of the vibration of the light waves.

portion of the extreme UV, including wavelengths shorter than the resonance line of hydrogen.[45] This instrument proved that some sources were observable in the extreme UV. The imaging telescope used an image intensifier with film. The ability to use and recover film allowed the astronomers to obtain numerous photographs in the UV of galaxies, clusters, and hot stars covering much more of the sky than the HST images. The BBXRT demonstrated the usefulness of a nest of many thin grazing incidence X-ray mirrors for imaging in the soft X-ray region.[46] Because they are very thin, many mirrors can be nested to provide a large collecting area with limited weight. This type of system is now being used on the European X-ray Multi-Mirror (XMM) satellite.

Another important way in which the Shuttle has accommodated scientific experiments is through the use of Spartan payloads. These are smaller satellites set free from the shuttle with their own instruments and guidance and tracking to operate for days rather than for the minutes provided by a sounding rocket. The satellites are then recovered by the shuttle crew and can be flown again on later missions. Spartan payloads have revealed their value in reacting to unexpected circumstances: an instrument to observe Comet Halley in the UV was prepared in fourteen months to fly on a Spartan when NASA realized HST would not be ready in time for the observations. Unfortunately, this Spartan was lost in the *Challenger* accident. An American-German UV spectrograph, available as a guest-investigator instrument, flew aboard a Spartan payload for fourteen days in 1996 and observed more than two hundred targets for

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[45] Only the Copernicus satellite had previously explored the region for which the instrument was optimized, and the shorter wavelength region had not been explored at all at that time.

[46] The energy ranges from 0.3 to 12 kiloelectron volts (keV). A keV gives the amount of energy the photon carries.

astronomers in a number of countries. Smaller experiments have been flown on a Hitchhiker bridge and still smaller experiments in Get Away Special cans.

There are thus both advantages and disadvantages to the use of humans to support astronomical instruments. The ability to compensate for the mirror problems on the HST and to upgrade both the spacecraft and the instruments every few years has certainly not only rescued a major mission but also enhanced its capability immensely. On the other hand, the design, testing, and paperwork requirements inherent to human launches make instruments flown on such missions extremely costly, at least the first time they fly. In addition, the use of the shuttle either confines an astronomy experiment to low-Earth orbit or requires an additional stage. Most astronomical observations benefit from being farther from Earth to provide longer, uninterrupted periods of observation and to avoid the thermal, radiation, and atomic environment of near-Earth space. At present, this fact makes revisits impossible, although some in NASA are considering the possibility of servicing spacecraft at the Lagrangian 2 (L2) point.[47] NASA is planning to send the Space Infrared Telescope Facility (SIRTF), as well as several other next-generation astronomical instruments, to this location.

Exploring the Spectrum

This essay now turns to a review of space astronomy and astrophysics in various regions of the electro-magnetic spectrum.

Gamma-ray Astronomy

Gamma rays have the advantage of being able to traverse the entire universe to the top of Earth's atmosphere with little absorption and, unlike cosmic rays, retain

[47] The L2 point is a point on the sun-earth line, beyond the Earth, at which a spacecraft orbits the sun with the same period as the Earth and hence remains in essentially the same position with respect to the earth.

information on the direction of their sources. Partly on the basis of an overly optimistic prediction of the intensity of cosmic gamma rays,[48] there were early, unsuccessful attempts to observe this radiation. Aside from their low intensity, a major problem with detecting gamma rays is that high-energy particles, both from cosmic rays and from the interactions of cosmic rays with the atmosphere, behave in the detectors much like gamma rays. Spacecraft themselves also contain small quantities of radioactive impurities that produce both gamma rays and high-energy particles. These background sources of radiation are much stronger than the gamma rays to be measured. Thus, in addition to good instrument sensitivity, it is essential to have excellent shielding and a way to determine the direction of arrival of the radiation.

The earliest attempts to observe cosmic gamma rays were with balloons.[49] Although these early flights were unsuccessful, the development of larger balloons capable of lifting heavier payloads to higher altitude led to many successful flights. Balloon studies have both made important discoveries and tested new approaches to instrumentation. For example, the electron-positron annihilation line at 0.511 million electron volts (MeV)[50] was first observed from a balloon.[51] However, the energy determination from these measurements was sufficiently uncertain that confirmation of the line position awaited the results from another balloon flight in 1981.

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[48] See, for example, Malcomb P. Savedoff, "The Crab and Cygnus A as Gamma-Ray Sources," *Il Nuovo Cimento* 10 (1959): 12-18.

[49] T. L. Cline, "Search for High-Energy Cosmic Gamma Rays," *Physical Review Letters* 7 (1961): 3.

[50] This spectral line results when an electron and a positron (positive electron) merge and are both destroyed in a burst of energy corresponding to their total rest mass.

[51] M. Leventhal, et al., "Gamma-Ray Lines and Continuum Radiation from the Galactic Center," *Astrophysical Journal* 240 (1980): 338-343.

Cosmic ray researchers at the Massachusetts Institute of Technology (MIT) began in the mid-1950s to study the directional intensity of cosmic gamma rays using detectors flown to high altitudes on balloons. Soon they realized that only with a satellite would they be able to conduct gamma-ray experiments that surveyed the entire celestial sphere and avoided the interference of atmospherically produced background radiation. In 1958, the MIT group, led by William Kraushaar, made a proposal first to the National Science Foundation and then to the Space Science Board of the National Academy of Sciences for a satellite-borne gamma-ray experiment.[52] [III-2] On April 27, 1961, Kraushaar's experiment was launched aboard Explorer 11, the first astronomical satellite. Explorer 11 may have detected several galaxies and strong radio sources, but the data were marginal: only one or two gamma rays were observed from each.[53]

During the 1960s, NASA initiated a scientific spacecraft series, the Orbiting Solar Observatories (OSOs), designed to be the first major space program to study the sun. The OSO satellites were essentially large gyroscopes. A heavy wheel stabilized the satellite, and two compartments rotated against the wheel to point at the sun continuously. The wheel not only contained the necessary spacecraft components, but also had room for non-solar experiments. The first reliable detection of high-energy cosmic gamma rays was from OSO-3, on which Kraushaar flew an improved version of the Explorer 11 instrument.[54] This experiment showed diffuse radiation to be

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[52] William L. Kraushaar to J. Howard McMillen, May 20, 1958; William L. Kraushaar, "Research and Budget Proposal to the Space Science Board of the National Academy of Sciences for the Support of a High-energy Gamma-ray Satellite-borne Experiment to be Performed by the Cosmic Ray Group of the Massachusetts Institute of Technology Laboratory for Nuclear Science," October 10, 1958.

[53] William Kraushaar et al., "Explorer XI Experiment on Cosmic Gamma Rays," *Astrophysical Journal* 141 (1965): 845. Interestingly, each source detected by Explorer 11 has since been observed in gamma rays.

[54] William Kraushaar, "Proposal to the National Aeronautics and Space Administration for the Support of the Development and Construction of an Instrument for Gamma Ray Astronomy to be Flown to the Orbiting Solar Observatory," November 8, 1962.

concentrated in the plane of the Milky Way, with a peak intensity in the direction of the center of the galaxy.[55] Although later satellites improved the details of the distribution, the basic results from this observation have not changed. The gamma rays detected in this experiment, for the most part, result from the interaction of cosmic rays with interstellar material. Later OSOs also provided important gamma-ray data.

An interesting and exciting cosmic gamma-ray discovery was made with Department of Defense satellites in 1969. The Vela series of satellites had been launched to monitor worldwide compliance with the treaty outlawing nuclear testing in the atmosphere or above ground. These satellites detected various brief bursts in soft gamma rays.[56] These bursts often lasted for a number of seconds, with the intensity varying rapidly and chaotically in a fraction of a second.[57] There were also a number of X-ray bursts observed with these satellites, but only two were coincident with gamma-ray bursts. These measurements had a major effect on the later NASA program, which included various spacecraft entirely devoted to the study of these events as well as specialized instruments on other spacecraft. For example, observations with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) have shown that the gamma-ray bursts are evenly distributed over the sky. The spatial coincidence of a gamma-ray burst, observed with the Italian-Dutch satellite, Beppo-Sax, with a following optical image permitted the identification of the source. A spectrum of this source proved that it was at a large, cosmological, distance from the

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[55] Carl E. Fichtel and Jacob I. Trombka, *Gamma-ray Astrophysics: A New Insight into the Universe*, NASA Reference Publication 1386, 2[nn] ed. (October 1997). Some other information in this section of the essay has also been taken from this book.

[56] The bursts had energies in the range 150 keV to 1.5 MeV.

[57] J. Terrell et al., "Observation of Two Gamma-ray Bursts by Vela X-ray Detectors," *Astrophysical Journal* 254 (1982): 279-286.

Milky Way. However, even after thirty years, there is still no understanding of the nature of these bursts. A completely different type of gamma-ray burst was discovered later. These bursts appear to originate within the Milky Way and repeat irregularly. They probably arise from highly magnetic neutron stars.

In the 1970s, NASA launched a series of scientific satellites called Small Astronomical Satellites (SASs). The second Small Astronomical Satellite (SAS-2), launched in 1972, carried a gamma-ray spark chamber that had about twelve times the sensitivity of the OSO-3 gamma-ray experiment and an angular resolution of a few degrees.[58,59] SAS-2 gave a detailed picture of the diffuse background, which astronomers determined was correlated with known structural features in the galaxy. SAS-2 also provided observations of a number of types of discrete sources, including pulsars.

NASA followed these satellites with the much larger High Energy Astrophysical Observatories (HEAOs).[60] [III-21] HEAO-1, launched in 1977, was primarily devoted to X-rays, but also carried a soft gamma-ray detector. Its primary result was a nearly complete survey of the sky. HEAO-3 carried a hard X-ray, soft gamma-ray experiment. This was a large germanium spectrometer designed to detect gamma-ray lines from various sources. These include the excitation and de-excitation of interstellar nuclei and the decay of nuclei created in excited levels in supernovae.[61] Thus, these observations

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[58] Resolution is extremely important for locating a source. It also helps distinguish a source from the background, so makes it possible to detect fainter sources. High angular resolution is the primary advantage of HST.

[59] COS-B, a European satellite launched in 1975, carried an instrument with approximately the same sensitivity and angular resolution.

[60] NASA, "HEAO Project Plan," June 13, 1973.

[61] The maximum mass for a white dwarf is about three times that of the sun. If a star is much heavier than that when it uses the last of its nuclear fuel, it condenses so rapidly that the material essentially bounces and most is ejected into space. Because this material had been near the core of the star it is very hot. Thus, the star becomes very large and bright, rivaling in brightness the brightness of an entire galaxy for short time. This outburst is called a supernova because it looks like a nova but is much brighter.

provide information on both the composition of sources and their physical natures. A team led by W. A. Mahoney observed aluminum in the galaxy.[62] Although it has roughly the same spatial distribution as the continuum radiation, the radiation from this long-lived isotope is more clumped. With the possible exception of the Vela supernova, the source of the clumps is unknown. This observation is providing information on the distribution of matter in interstellar space, although we do not yet understand the significance of the clumping.

In the 1970s NASA began planning for its next gamma-ray astronomy satellite. The result, the Compton Gamma Ray Observatory, was launched in 1991 as the second of NASA's Great Observatories. This mission is discussed in greater detail in the subsequent section on the Great Observatories. Thus, gamma-ray astronomy experienced a twelve-year gap between launches of missions; some balloon investigations, however, continued during the interim.

X-ray Astronomy

Encouraged by the observations of X-rays from the sun by Herbert Freidman and his associates at NRL, astronomers made early attempts with sounding rockets to detect non-solar X-rays.[63] Not surprisingly, since even Alpha Centauri (Capella), the nearest star (and a solar twin), would have been too faint to be observed, it was not until 1962 that cosmic X-rays were detected by Riccardo Giacconi and his colleagues at American

[62] W. A. Mahoney, "HEAO-3 Discovery of ^{26}Al in the Interstellar Medium," *Astrophysical Journal* 286 (1984): 578-85. Specifically, the team observed the ^{26}Al line at 1.809 MeV.
[63] H. V. D. Bradt, "X-ray Astronomy Missions," *Annual Review of Astrophysics* 30 (1992): 391-427. Many portions of this section are based on this source.

Science and Engineering.[64] Giacconi had been urged to search for celestial X-ray sources by MIT physicist Bruno Rossi, who believed that searching the universe in the Xray region would enable astronomers to peer further into the universe than they had been able to see in other wavelengths. Using a spinning rocket and Geiger counters, Giacconi's team observed a strong Xray source near, but probably not coincident with, the galactic center, and a second source in the vicinity of Cassiopeia-A and Cygnus-A, two strong radio sources.[65] The poor angular resolution of the detectors and the uncertainties in the direction of the sources precluded a closer identification. In addition, the team observed a diffuse Xray background. The following year, Giacconi's group made a proposal to NASA to pursue a program of extra-solar X-ray astronomy studies.[66] [III-8] Later rocket observations located these sources more accurately.[67]

Subsequent NASA and non-NASA X-ray studies built on the work of Giacconi's 1962 experiment. Harder, or higher energy, X-rays were too weak to be observed in the short time available with sounding rockets, but could be observed from balloons; high-energy X-rays from the Crab Nebula, for example, were detected using balloons.[68] OSO-3 observed the hard X-ray diffuse background, and later OSOs also carried X-ray experiments that produced important results, including OSO-8's measurement of iron-

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[64] Richard Giacconi et al., "Evidence for X-rays from Sources outside the Solar System," *Physical Review Letters* 9 (1962): 439-443.

[65] The first radio sources to be discovered were given the names of the constellations in which they occur, followed by a letter, with A for the first source. Thus, the Crab Nebula is Taurus A. The constellation name is usually abbreviated to three letters. Sources of X-ray emission discovered early followed a similar naming scheme. Thus, the first X-ray source discovered was Sco (Scorpio) X-1.

[66] American Science and Engineering, "An Experimental Program of Extra-Solar X-ray Astronomy," September 25, 1963.

[67] In 1963, NRL studies confirmed the detection of celestial X-ray sources and pinpointed the source near the galactic center source, which became known as Sco X-1.

[68] Balloons are still used both to observe hard X-rays and to test new instrumentation for detecting both hard X-rays and gamma rays.

line emission. Later in the 1960s, scientists detected X-rays from galaxy M87, proving that X-ray astronomy could allow astronomers to study objects beyond this galaxy.

The first satellite exclusively devoted to X-ray astronomy was the SAS-1. This spacecraft was launched from an Italian platform off the coast of Kenya to minimize problems with the Earth's radiation belts. It was named *Uhuru*, the Swahili word for "freedom," in honor of its launch on Kenya's Independence Day, December 12, 1970. [III-17] It carried several proportional counters.[69] The satellite rotated slowly, thus monitoring the entire sky and having enough time in a given pointing direction to detect sources up to a thousand times fainter than the Crab Nebula.[70] The final *Uhuru* catalog contained 339 objects, representing most of the common types of X-ray sources. Particularly interesting were the many binary sources in which X-rays were produced by *bremsstrallung*, or braking radiation, with material from one source impacting a compact companion.[71] Such sources play a major role in high-energy astronomy. One *Uhuru* source, Cyg (Cygnus) X-1, later detected optically, was found to be heavy enough that the compact object must be a black hole, thus providing convincing, if indirect, proof that black holes exist.

Observational X-ray astronomy was quite active between *Uhuru* and the launch of the first HEAO in 1977. Many observations were made from both sounding rockets and satellites. Launched in 1972, OAO-3, also called *Copernicus*, carried small grazing incidence mirrors that fed an X-ray proportional counter. The Netherlands Astronomical

[69] The proportional counters were sensitive to the energy range 2 to 20 keV and had angular resolution of one by ten degrees.
[70] Intensities in X-ray astronomy are often given in units of the intensity of the Crab Nebula. This unusually stable object is usually the brightest X-ray source in the sky.
[71] This braking radiation results from the conversion of kinetic energy to thermal energy when rapidly moving material is stopped suddenly.

Satellite (ANS) carried both X-ray and ultraviolet experiments. OSO-7 and OSO-8 also carried several X-ray experiments. Among other things, these experiments showed that the intensity of Cen (Centaurus) A, an active galaxy, had changed by a factor of four in less than two years, confirmed that X-ray bursts displayed a black body spectrum,[72] and detected iron-line emission from several clusters of galaxies. ANS showed that bursting X-ray sources do not pulsate and that pulsating X-ray sources do not burst. A rocket instrument showed that radiation from the Crab Nebula is polarized, thus confirming its synchrotron source.[73] An image of the Cygnus loop, a supernova remnant, clearly showed shock waves. Emission from the corona, the hot, outermost region of a star, was observed from Capella, and soft X-rays were observed from a white dwarf star. Oxygen that had lost six electrons was detected in the diffuse background, thus confirming the thermal origin of the soft X-ray background and the ultraviolet result from *Copernicus*.

In 1974, Ariel 5, built by the British, carried a NASA pinhole X-ray camera. Both long-period pulsars and bright transient sources were discovered with this satellite. NASA's SAS-3, launched in 1975, could be spun slowly or pointed for up to thirty minutes. The first highly magnetic white dwarf binary was discovered with this satellite. It also provided precise locations for about sixty X-ray sources and a survey of the soft X-ray background.[74] These examples represent only a few of the many exciting discoveries made during this time.

The HEAO program in 1977 opened the era of large, high-energy instruments. These spacecraft were 2.5 by 5.8 meters in size, weighed about 3,000 kilograms, and had

[72] A black body is an object that is a perfect absorber of radiation.
[73] That is, the radiation came from rapidly moving electrons in a magnetic field.
[74] The survey was conducted between 0.1 and 0.28 keV.

a high telemetry rate. The first had a limited pointing capability, used in its last year of operation, but was intended primarily for surveys. A proportional counter array with about the same sensitivity as *Uhuru* produced a catalog of 842 sources. The large area of the detector permitted searches for rapid brightness variations. One result was the discovery of irregular variation in Cyg X-1, with time scales down to three thousandths of a second. A smaller proportional counter array covered a broad higher energy region.[75] A catalog of 85 high-latitude sources yielded improved X-ray brightness for active galactic nuclei and clusters of galaxies. This experiment showed that all quasars[76] emit X-rays. Particularly surprising was the detection of 100-second variability in a Seyfert[77] galaxy. A catalog of 114 soft X-ray sources was also produced. Positions were determined to about one arcminute, leading to several hundred optical identifications. The fourth experiment on this satellite was a high-energy experiment that produced a catalog of about 40 high-energy sources.[78]

The second pointed X-ray experiment, and the first to use moderately large grazing incidence optics, was carried on the second of the HEAOs, later named *Einstein*. Such optics produce true images like those in common photographs, but can only focus on moderately soft X-rays. Any one of four instruments could be rotated into the focal plane of the telescope.[79] The good resolution and imaging capability provided high

[75] This was the region between 0.2 and 60 eV.
[76] A quasar is the extremely bright nucleus of an active galaxy. It may outshine the remainder of the galaxy in the optical region and is bright in all other wavelengths as well. It may be evidence of material interacting with a black hole many millions of times more massive than the sun compressed into the volume whose radius is about 1/10 times the distance of the earth from the sun.
[77] A Seyfert galaxy is an active galaxy with a bright nucleus but the least luminous of active galaxies. The rapid variability indicates that the radiation comes from a region that light can traverse in 100 seconds, that is, less than 3000 kilometers.
[78] The sources had energies between 0.025 and 10 MeV.
[79] An imaging proportional counter with high sensitivity and resolution near one arcminute, an imager with four-arcsecond resolution, a solid state spectrometer with appreciably higher spectral resolution than a proportional counter, and a Bragg crystal spectrometer with high spectral resolution.

sensitivity to weak point sources as well as to extended images, such as nebulae. The sensitivity and resolution of *Einstein* made observations in the X-ray region comparable in power to those in other wavelength regions. Much new information resulted. This was the first satellite to have a major guest-observer program.

Although other countries launched small X-ray astronomy satellites during the period, NASA launched no X-ray missions in the 1980s.[80] During that time, international cooperation in X-ray astronomy played a more major role and extensive guest-observer use of the instruments became common. In 1982, NASA agreed to work with Germany and the United Kingdom on the Roentgen Satellite (ROSAT), an X-ray observatory. The SAO provided the High Resolution Imager. This mission emphasized softer (less energetic) radiation.[81] In six months of scanning, ROSAT observed more than 150,000 discrete sources at higher energies and 479 in the soft band. The latter were primarily late-type, or cool, stars and white dwarfs (comparatively near the sun).

NASA continued to participate in international missions throughout the 1990s. The fourth Japanese satellite, the Advanced Satellite for Cosmology and Astrophysics (ASCA), concentrated on the 0.4 to 10 keV range, using four nests of thin grazing incidence mirrors feeding two cameras and two spectrometers. Astronomers at NASA's Goddard Space Flight Center and MIT contributed instruments. As one of numerous examples of the sensitive spectroscopy from this satellite, it has produced much new knowledge of supernova remnants. Among other things, it has also located many previously unknown neutron stars associated within supernova remnants, thus solving the

[80] During this time, however, NASA continued to carry out work begun in 1976 on a large X-ray spacecraft, the Advanced X-ray Astrophysics Facility, or Chandra, which was launched in 1999.
[81] A wide field camera on this mission was sensitive from 62 to 206 eV; a higher resolution camera was sensitive from 0.1 to 2.5 keV.

mystery of the apparent scarcity of these stars after supernova explosions. It has found synchrotron radiation in the outer regions of these remnants, apparently resulting from electrons accelerated strongly in shocks. This indicates that these may be the sites of cosmic ray acceleration.

The European X-ray Multi-Mirror (XMM) telescope was launched in December 1999. It carries a dense nest of thin grazing incidence telescopes that provide an unusually large collecting area for its diameter. It is not competitive with Chandra (discussed below) for imaging, but complements Chandra by providing excellent spectroscopic capability. It can also image sources in the X-ray, UV, and visible simultaneously. The visible limiting magnitude can be appreciably deeper than from the ground. Scientists from Columbia University and the University of California at Santa Barbara provided parts of the instruments.

NASA's first satellite dedicated to the extreme UV was the Extreme Ultraviolet Explorer (EUVE). This satellite carried three grazing incidence telescopes.[82] Surprisingly, more than twenty extragalactic sources were observed in directions with low hydrogen absorption. All of these sources are have active galactic nuclei; at least one is a quasar. In fall 2000 NASA decided to de-orbit EUVE, not due to its inability to continue returning excellent science but because of budget constraints.

The Rossi X-ray Timing Explorer (RXTE), launched in 1995, is currently measuring the variability over time scales from milliseconds to years in the emission of

[82] Each of the survey telescopes carried two band pass filters; together they surveyed the sky at 100, 200, 400, and 600 angstroms. Three spectrometers provide spectra from roughly 70 to 760 angstroms with a resolution $\lambda/\Delta\lambda \sim 300$ (λ stands for wavelength). Of course, this equation also works for frequency and energy.

X-ray sources in a wide energy range.[83] Most X-ray sources vary in brightness. The variation in brightness can tell a great deal about the nature of each source. The RXTE can also point to a chosen source rapidly to observe short-lived phenomena. This satellite has discovered kilohertz quasi-periodic objects (QPOs),[84] and, from a detailed study of a bursting pulsar, provided a stringent test of the way material falls onto a compact object.

In July 1999, NASA launched its most sophisticated X-ray spacecraft ever. Originally called the Advanced X-ray Astrophysics Facility (AXAF), this satellite was renamed the Chandra X-ray Observatory in honor of astronomer Subrahmanyan Chandrasekhar. One of the space agency's Great Observatories, this spacecraft is discussed in greater detail below.

Optical Astronomy[85]

Observations in the visible wavelengths from space offer two advantages over similar observations from the ground: freedom from atmospheric turbulence and lack of the air glow background.[86] Taking advantage of either of these improvements required longer exposures with better pointing than could be obtained with rockets; balloons, however, offered the possibility of observations from above the atmospheric turbulence that blurs the images. Princeton University astronomers developed two programs to exploit this capability. First, under Office of Naval Research sponsorship, Princeton scientists flew a 30-centimeter telescope to observe the sun. The results were spectacular

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[83] This included the energy range from two to 250 keV.
[84] QPOs are objects that vary in brightness nearly, but not exactly, regularly.
[85] In this essay, "optical" includes the far UV, UV, and visible. That is, it includes the region between the hydrogen continuum and the red part of the spectrum in which atmospheric molecules begin to cause serious absorption.
[86] Background sources beyond the earth's vicinity do remain, however.

and proved the advantage of observations above the atmosphere. This success led to the development of a NASA-supported, balloon-borne, 91-centimeter telescope for other celestial observations called Stratoscope II. [III-7] Led by Martin Schwarzschild, the Princeton team obtained excellent images both of planets and nuclei of galaxies. However, while these flights proved the possibilities of the technique, they were much more complex and expensive than had been expected, and the effort was dropped after several flights of the 91-centimeter telescope.

In the 1960s and 1970s, NASA commenced a very active rocket program of studies of stars and galactic nebulae in the UV. Sounding rockets were also used to test new instrument techniques before they were used on satellites. According to NASA Goddard Space Flight Center astronomer Theodore Stecher:

> The first flights were ultraviolet photometry where only the spin of the Aerobee rocket was controlled. These photometers covered a large fraction of the sky as the rocket spun and precessed in free fall. The rigid body problem was solved after the flight in order to ascertain which stars had been observed.[87] This technique was then extended to spectra with objective grating spectrometers where the controlled spin of the rocket did the spectral scans. These early UV observations provided information on the stellar energy distributions and also the nature of the interstellar extinction. The astronomers and other technical staff learned how to build experiments and how to make them work. An attitude control system was developed in stages with Goddard programs serving as the trial flights in many cases. First it was a stable platform. Then [it] could point an instrument at bright stars. And finally, a stable offset pointing system

[87] That is, the standard rules governing the behavior of an inflexible body were used to understand the motion of the rocket.

> enabled the astronomer to observe anything that his instrument could detect.[88]

With the availability of the International Ultraviolet Explorer and, particularly, the Hubble Space Telescope, the UV sounding rocket program decreased in importance. A few are still used in this spectral region, particularly for solar system objects and targets of opportunity, but the cream provided by bright sources has been skimmed and longer exposure times than those available from rocket flights are required to investigate most modern problems in astronomy.

Balloons do not float high enough to make observations in the UV region, but it appeared that NASA's high-altitude experimental airplane, the X-15, could. Arthur Code, an astronomer from the University of Wisconsin, replaced one of the cameras normally carried on the plane with a two-channel UV photometer. Code explained:

> I was traveling [in the late 1950s] to one of many committee meetings when I noticed a sliver of sunlight on the back bulkhead of the plane. I went back and measured the motion of the light and of the distance from the window to the bulkhead and concluded that the autopilot was holding the aircraft steady to within a minute of arc. I looked out the window and the sky was a clear dark blue; certainly you could observe from such a platform. If only the plane could get above the ozone layer we could check on the UV flux of stars in a conventional way, we could get images using UV sensitive photographic emulsion. We approached NASA about utilizing the X-15 rocket plane. With the help of Ernest Ott at NASA Headquarters, this project was approved and we started by replacing one of the on-board movie cameras located in a bubble on the fuselage with a two-channel photometer providing a visual and a UV band pass. This photometer provided measurements of the sky brightness below and

[88] Theodore Stecher, personal communication.

> above the ozone layer. Martin Burkhead's Ph.D. thesis utilized this data to map the UV sky brightness. During this time we contracted with Astronautics Corporation of America to develop a pointing system for the aircraft. The gyro-stabilized pointing system replaced the instrument elevator located behind the pilot compartment on the X-15. As the plane moved into ballistic flight the hatches were opened and the cockpit flyball was biased so that if the pilot centered the needles, the line of sight was directed to the desired star position. A star tracker then took command of the platform position. We had mounted both UV cameras and a spectrograph on the platform. Observations from the X-15 showed no halos.[89] We also obtained the first UV photometry of a late-type star, Antares.[90]

Unfortunately, the modified X-15 crashed on its third flight; when it was rebuilt, NASA designed it for speed rather than altitude. It no longer appeared to be worth continuing the program.

When the United States was formulating plans for the International Geophysical Year (IGY) in 1954 and 1955, the National Academy of Sciences asked scientists to propose instrumentation for scientific investigations that they would like to conduct from a satellite. Four astronomers responded. Code proposed an UV photometer; Fred Whipple, from the SAO, proposed a television map of the sky in the UV; Leo Goldberg, from Harvard, proposed a UV telescope for studying the sun; and Lyman Spitzer, from Princeton University, proposed a high-resolution UV spectrometer. Although they were scientifically interesting proposals, each of these instruments was too large for the small satellite the United States was developing for the IGY.

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89 Based on early rocket observations, astronomers had announced that they observed halos around the few bright stars that they could measure. J. E. Kupperian et al., "Observational Astrophysics from Rockets I: Nebular Photometry at 1300 Angstroms," *Astrophysical Journal* 128 (1958): 453.
90 Arthur Code, personal communication.

Almost immediately after the establishment of NASA, these proposals were revived. It was clear that the four experiments shared major characteristics. They were comparatively large (although the experiments from Code and Whipple were somewhat smaller than that from Spitzer) and each, except for Goldberg's, required the ability to aim the instruments accurately at any point in the sky and to hold that aim for a significant period of time. Of course, they also shared the requirements common to all space experiments, such as a way to collect the data and transmit it to the ground, a power supply, and a capability to command the spacecraft and the experiment. Because of the common pointing requirements, it was decided early that a standard spacecraft design would serve each experiment with very minor modifications. Moreover, the Code and Whipple experiments were sufficiently compact that they could share the same spacecraft, by pointing out opposite ends. Soon it was realized that the thermal characteristics of an experiment pointing to the sun were so different from those of the other experiments that Goldberg's experiment was incompatible with the same spacecraft design, and thus this experiment was postponed to the Advanced Orbiting Solar Observatory (AOSO), then under discussion.[91] In its place, NASA substituted a low-resolution spectrograph fed by a 91-centimeter mirror, proposed by James Kupperian from Goddard. Thus three missions were definitely planned and NASA expected that there would be a continuing series following these, with minor modifications leading up

[91] AOSO was never developed. Eight OSOs, with increasing capability, were eventually flown. Skylab followed. This human mission produced spectacular results in the X-ray region, the UV, and the visible. It was not until the 1990s that any other major solar satellites, produced with international cooperation, were launched. Goldberg never did fly an experiment although he remained interested in the space program. Solar research is discussed in Volume VI of this series.

to a larger primary mirror, possibly 1.5 meters in diameter. The resulting satellites were the OAOs, discussed earlier in this essay.[92] [III-5, III-6]

As was often the case, particularly early in the program, the technological problems proved more difficult than had been expected. All except the problems with the vidicons (television tubes) were solved with a three-year slip of the originally planned first OAO launch from 1963 to 1966.[93] Television tubes for the visible region were common and it was not expected that the change to an UV-sensitive cathode would be difficult. This change of cathode indeed did not present a problem, but it was necessary for the tube to be evacuated. Because glass does not transmit the UV, the UV radiation from stars had to pass through a quartz or lithium fluoride window. The entire tube could not be built of these materials, and the problem of sealing such a window to a metal tube proved to be nearly intractable. Although this problem was finally solved in time for the first successful OAO launch in 1968, the tubes never did perform as well as had been hoped.

The first OAO mission was to carry the experiments of Code and Whipple. In spite of the delay in the Whipple experiment, NASA decided to go ahead with the launch. That meant a hasty substitution for the SAO experiment. Phillip Fisher of Lockheed Missiles and Space Systems had developed an X-ray experiment that proved to be suitable; a prototype of the Explorer 11 gamma ray detector also could be used. Thus an X-ray and a gamma-ray instrument substituted for the SAO instrument in 1966. Despite

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[92] Homer Newell to Abe Silverstein, "Proposed NASA Project—Orbiting Astronomical Observatories," March 16, 1959, with attachment, March 12, 1959.

[93] Many technological innovations from OAO were the bases of future developments. For example, IBM later used the magnetic core memory data storage system it developed for the OAOs for a series of its mainframe computers.

a satisfactory launch, a problem in the power supply system of the spacecraft prevented the acquisition of any useful data from this mission.

A prototype of the Code experiment, along with Whipple's experiment, was flown on another OAO spacecraft in 1968; this was the first successful OAO mission. The SAO experiment produced a catalog of UV fluxes from more than 100,000 stars. The Wisconsin experiment made several important discoveries. Perhaps the most interesting was the confirmation and more detailed study of the peak in the interstellar opacity near 220 nanometers. The presence of graphite (carbon) is probably the primary cause of this opacity, but other elements may be present. The results also showed that spiral galaxies are appreciably brighter in the UV than had been expected, indicating the presence of numerous faint blue stars.

The Goddard experiment was launched in 1970, but, unfortunately, a technician had tightened a bolt on the shroud of the Goddard payload too much. The shroud did not come off as it was supposed to, and the satellite did not achieve orbit. Spitzer's experiment flew on an OAO mission launched in 1972 that became known as *Copernicus*. Until the launch of NASA's Far-Ultraviolet Spectroscopic Explorer (FUSE) in 1999, the Princeton spectrometer was the only free-flying satellite that could observe the far UV, and the only instrument that could obtain good spectral resolution. From the observation in this spectral region of oxygen that has lost five electrons, Spitzer and his colleagues determined that much of interstellar space is filled with a hot, ionized medium at about 300,000 degrees Celsius. This is not only hotter than many regions of interstellar space, where temperatures are lower than 100 degrees Celsius, but also hotter than the ionized gas near hot stars, whose temperatures reach 10,000 degrees Celsius.

Early in the planning for a European space science program, the European Space Research Organization (ESRO) had proposed an astronomical satellite similar to the OAO and had let a contract to United Kingdom astronomer Robert Wilson to design the satellite. Budgetary limitations, however, prevented the development of such a satellite by Europe. The failure of the 1970 OAO mission left UV astronomy with no low-resolution UV spectrometer or any spectrometer that could observe moderately faint stars. Wilson and Albert Boggess, the Goddard scientist who had replaced Kupperian on the OAO experiment, realized that if the United Kingdom and the United States pooled their planning, they might be able to amass the funds necessary to build an ultraviolet spectrometer.[94] Moreover, they could take advantage of technological developments since the planning of the OAOs. They estimated that with a low-resolution spectrometer, they could obtain spectra of the brightest quasar, 3C273. A vidicon would be used to detect the spectra.

A major innovation of the project was to place the satellite in a synchronous orbit. Since this orbit permits continuous communication with the satellite, astronomers could work with the satellite in the same way they were used to working with telescopes on the ground, changing the conditions of the exposure in response to the data and even changing the order of the program. A second advantage was that in the higher orbit the Earth blocked less of the sky. Moreover, whereas a spacecraft in low orbit could only yield thirty- or forty-minute exposures at a time, in synchronous orbit it could observe a source for as long as eighteen hours without needing to re-point to the object.

[94] They proposed a spectrometer with two resolutions, a low resolution of about 0.7 nanometers and a high resolution near 0.1 to 0.3 nanometers.

This proposal resulted in the International Ultraviolet Explorer (IUE).[95] Funding came from not only the United States and the United Kingdom, but also from the European Space Agency (ESA), which replaced ESRO in 1975.[96] ESA established a tracking station in Spain that controlled the satellite eight hours a day while it was closer to Europe than to the United States, and also contributed to the calibration and reduction of the data. Launched in January 1978, IUE was almost immediately opened to the use of any astronomer with a satisfactory proposal. There were no restrictions based on country of origin, and even while the Cold War was still in progress, observers from the Soviet Union and China participated. About half of the world's astronomers used this telescope during its twenty-year life.[97] The possibility of obtaining observations in much the same way as ground-based astronomers were used to working largely overcame their earlier reluctance to get involved in space astronomy.

The sensitivity of IUE's spectrometers was surprisingly high. Not only was it possible to reach the brightest quasars, but a number of fainter ones were also accessible.[98] The results from IUE touched almost every field of astronomy. The satellite measured water on Mars, aurorae on Jupiter, spectra of hot stars and of stars with peculiar spectra, the chromospheres[99] of cooler stars like the sun, many types of variable stars, and the nuclei of active galaxies.[100] [III-30] In all, as of August 2000, 3,600

[95] NASA had originally referred to the satellite as SAS-D.

[96] Memorandum of Understanding between the European Space Research Organisation and the United States National Aeronautics and Space Administration, March 12, 1974.

[97] Yoji Kondo, "The Ultraviolet International Explorer (IUE)," in Yoji Kondo, ed., *Observations in Earth Orbit and Beyond* (Boston, MA: Kluwer Academic Press, 1990), pp. 35-40.

[98] *Ibid*. The faintest source observed was seven magnitudes fainter than 3C273, i.e., more than 600 times fainter.

[99] The chromosphere is the region of a stellar atmosphere just outside the apparent surface (as seen in the visible region). It is the coolest region of the stellar atmosphere, but also contains very hot active regions.

[100] Thomas A. Mutch to NASA Administrator, "IUE Post Launch Report #2," August 16, 1979.

scientific papers had resulted from observations made with this satellite.[101] Because of budget constraints, IUE was turned off after twenty years of operation, still working well; active use of the data continues.

NASA's FUSE mission, launched in 1999, investigated the far-UV region.[102] A key question in this region is the ratio of deuterium[103] to common hydrogen. This ratio is determined cosmically by the mass-density of the universe. However, as deuterium and common hydrogen are both destroyed in stars, with deuterium being destroyed faster than common hydrogen, only an upper limit to the original value can be determined. As might have been expected, observations with FUSE have shown that the ratio in the interstellar medium, as seen against hot stars, varies from star to star; it is surprising that the ratio varies by about fifty per cent over scales possibly as small as thirty light years.[104] Several decades ago, radio astronomers discovered clouds of neutral hydrogen high above the galactic plane which were falling into the plane at high velocities. Surprisingly, FUSE observed that many of these clouds also contain oxygen that has lost three electrons, indicating that they also contain highly ionized gas.[105] The explanation for this combination of neutral hydrogen and highly ionized oxygen is unclear.

The most powerful satellite devoted to optical observations is the HST. Politically and possibly technically the most complex scientific satellite to date, this spacecraft is one of NASA's Great Observatories and is discussed in detail below.

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[101] Yoji Kondo, personal communication.

[102] In the 91.2-to-120-nanometer region, the resolution, $\lambda/\Delta\lambda$, is about 30,000; it is more moderate in the remainder of the range. W. Moos, "Lyman and the Far-Ultraviolet Spectroscopic Explorer," in Yoji Kondo, ed., *Observations in Earth Orbit and Beyond* (Boston, MA: Kluwer Academic Press, 1990), pp. 171-176.

[103] The nucleus of common hydrogen is a proton; the nucleus of deuterium contains a neutron also and thus is twice as heavy as hydrogen. It is often known as heavy hydrogen.

[104] M. Lemoine et al., "Deuterium Abundances," *New Astronomy Letters* 4 (1999): 231-43.

[105] W. Moos, "Overview of the Far-Ultraviolet Violet Spectroscopic Explorer," *Astrophysical Journal Letters* 538 (1999): 1-6.

Infrared Astronomy

Parts of the near-IR region and longer wavelengths are observable from the ground, but the atmosphere is opaque in much of the region.[106] This region of the spectrum was the last to be explored from space. The lack of sensitive detectors was a major constraint. Largely as a result of research sponsored by the national security community, good infrared detectors gradually became available. As in the gamma ray region, background noise is a major problem in the infrared, although the source of the background is very different. All material above the temperature of absolute zero[107] emits at all wavelengths in an amount that depends on the material's temperature. Although hotter bodies emit more at every wavelength than cooler ones, the highest relative emission for bodies between 1500 and 3 Kelvin (K) is in the IR.[108] Thus the telescope used to collect celestial IR radiation also radiates, providing an unavoidable background. This background can be lessened by cryogenically cooling the telescope. The detectors must also be cooled both to increase their sensitivity and to decrease the background. The atmosphere above the telescope also provides an inescapable background at airplane and balloon altitudes.

A great deal of the preliminary information in this spectral region has been obtained from aircraft and balloons, both of which are still used extensively.[109] The first

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[106] Water vapor and other molecules cause problems in the IR, particularly for wavelengths longer than one micrometer (1×10^{-6} meter). The atmosphere is opaque in most of the region between 25 and 1000 micrometers.
[107] Absolute zero is the temperature at which all atomic motion ceases.
[108] Kelvin (K) indicates that the temperature is measured on the Centigrade scale from absolute zero (-460 degrees Fahrenheit). Human body temperature is about 310 K. Kelvin temperature is 273 degrees greater than the Centigrade temperature.
[109] Balloons are used, particularly, in Antarctica where the air is very cold and dry.

IR observations of objects other than the sun were made from a business jet airplane flying at an altitude of fifteen kilometers. Most of the absorption of the atmosphere in the IR is by water vapor. Although there is still some water above the altitude at which the plane flew, most is below; the average transmission is of the order of sixty to eighty per cent in the mid-IR.[110] The plane carried a gyro-stabilized, thirty-centimeter telescope mounted in the aft escape hatch, without a window. Early flights showed that the IR emission from the Orion Nebula was from dust, and that both the center of the Milky Way galaxy and that of a Seyfert galaxy were very bright in the IR. NASA conducted eighty-five flights with this system between October 1968 and January 1971.[111] Among many other results, observations confirmed that the cosmic background is a blackbody source at a temperature less than 3 K.[112] The success of the airplane program led to the construction of a 91-centimeter telescope that was mounted in a modified C-141. With its first flight in 1974, this Kuiper Astronomical Observatory (KAO) was used extensively until it was decommissioned in 1995. Results covered a broad range of areas including detailed studies of dust clouds, emission nebulae, cool stars, and galaxies. Also, as for its predecessor, it played a major role in the development of instruments and techniques.

Advantages of airborne instrumentation compared to experiments carried by other space platforms include mobility, almost no restriction on weight and support resources, and access to the instrument during flight. The KAO also provided frequent flight opportunities, typically about seventy research flights per year, each of 7.5 hours in

[110] H. H-G. Aumann, *Airborne Infrared Astronomy* (Rice University Ph.D. thesis, 1970), (Ann Arbor, MI: University Microfilms, 1973).
[111] F. J. Low, “Airborne Infrared Astronomy: The Early Years,” Airborne Astronomy Symposium, NASA Ames Research Center, NASA Conference Publication 2353 (1984): 1-8.

duration.[113] The success of this program led to the development of the Stratospheric Observatory for Infrared Astronomy (SOFIA), a three-meter telescope on a Boeing 747SP, being constructed jointly by Germany and the United States.

Airborne instruments are good for studying point and angularly small sources and quickly responding to targets of opportunity. Nevertheless, they can only study small regions in which they can rapidly switch between the source and a neighboring area unaffected by the source in order to determine what fraction of the brightness observed from the source region results from the background. Since the background varies from one area to another, the comparison must be done very near the source. Theory predicted that it should be possible to observe the result of the "big bang" at the time electrons and atomic nuclei started to combine. Because of the expansion of the universe, this originally very hot radiation should now appear to be only a few degrees above absolute zero. Although the black body nature of this cosmic microwave background (CMB) was approximately established from aircraft measurements, a detailed study of this background could not be conducted at airplane altitudes. Balloons reach altitudes more than twice as high with a corresponding decrease in atmospheric background. Thus, balloon observations have complemented aircraft observations. They have been particularly useful in studies of the CMB. Although there were still problems with the result, Weiss and Muehlner published their observation in the *Physical Review* in 1973.[114]

Sounding rockets have played a smaller role in IR astronomy than in the UV and X-ray regions, although a number were flown. The Air Force Geophysical Laboratory

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[112] P. E. Boynton and R. A. Stokes, "Airborne Measurements of the Temperature of the Cosmic Microwave Background at 3.3 mm," *Nature* 247 (1974): 528-530.

[113] H. P. Larson, "The NASA Airborne Astronomy Program: A Perspective on its Contribution to Science, Technology, and Education," *ASP Conference Series* 73 (1995): 591-607.

produced a catalog of 2000 sources using data from rocket flights but this was somewhat a *tour-de-force*. Time at high altitude for a rocket is too short to allow adequate outgassing of instruments. Residual water vapor was a major problem and most of the rocket flights produced little useful data.

The first satellite to study the infrared was not launched until 1983. This satellite, the Infrared Astronomy Satellite (IRAS), was a joint effort among the United States, the Netherlands, and the United Kingdom. The Netherlands built the satellite and two small instruments, the United States built the major instrument and provided the launch, and the United Kingdom assisted with the data. The primary mission of the satellite was to provide a photometric survey of the sky in four wavelength regions.[115] Care was taken to eliminate signals from charged particles and nearby dust by requiring that a source be seen twice within seconds. Extraneous objects at medium distances were eliminated by duplicate observations within hours, and asteroids were identified by repeats six months later. The telescope and detectors were in a well-shielded dewar (a container that keeps things hot or cold like a thermos bottle) filled with liquid helium at a temperature of 1.8 K.[116] The IRAS catalog contained 250,000 sources, including both point sources and extended sources. IRAS also obtained spectra for the brighter of these sources. Thus, after a long wait, astronomers had an excellent map of the IR sky. It remains for the fourth Great Observatory, the Space Infrared Telescope Facility (SIRTF), still under construction, to both observe fainter sources and obtain more spatial and spectral detail of interesting objects.

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[114] Weiss and Muehlner completed their work before Boynton and Stokes had published their measurement.
[115] The wavelength regions were near 12, 25, 60, and 100 micrometers.

IRAS was unsuited to studying the CMB. The Cosmic Microwave Background Explorer (COBE), launched in 1989, made a major advance on this problem. [III-22] It carried three instruments to make different, complementary observations of the background. One instrument, the Far-Infrared Absolute Spectrometer (FIRAS), compared the CMB to an accurate black body.[117] This experiment demonstrated that the background radiation is extremely close to that of a black body over a broad range of wavelengths.[118] The Differential Microwave Radiometer (DMR) was designed to search for primeval fluctuations in the brightness of the CMB radiation.[119] The Diffuse Infrared Background Experiment (DIRBE) was designed to study the cosmic IR background.[120] While DIRBE put only upper limits on this background, it mapped the entire sky in ten IR wavelengths. The plane of the Milky Way galaxy was particularly obvious. The observations confirmed that this plane is slightly warped, as had been suggested earlier from radio observations, and indicated that the Milky Way is a barred spiral in shape. It also provided important information on the distribution of interplanetary dust.

The United States participated in the development of two IR satellites built by other nations and launched in 1995. One from Japan, the Infrared Telescope in Space, which had a small mirror, was optimized for studies of low surface-brightness objects. It carried two spectrometers for the near IR, a spectrometer for the mid-IR, and a

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[116] One Dutch instrument provided low-resolution spectra in the region 11 to 22.6 micrometers: the other Dutch instrument provided high spatial resolution (1 arcsecond) in a nine-by-nine-arcsecond field at 50 micrometers and 100 micrometers.

[117] FIRAS has two spectrometers with about 5 percent resolution covering the wavelengths 0.1 to 10 millimeters. The instrument was cooled to 1.5 K.

[118] Specifically, the temperature is 2.726 K +/- 0.010 K.

[119] The DMR had two channels in each of two wavelength regions: 31.5, 53, and 90 Gigahertz that compare 7-degree beams 60 degrees apart. Very small variations were observed that probably indicate the density variations that led to the development of galaxies early in the history of the universe.

[120] The DIRBE measured radiation at 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 micrometers. The Cosmic Infrared Background is at shorter wavelengths than the CMB and results both from the cosmic red shift and reprocessing of radiation by dust. It comes from a younger region of the universe than the CMB.

photometer for the far IR. A European satellite, the Infrared Space Observatory, which had a larger, cooled mirror, performed spectroscopy, imaging, photometry, and polarimetry at a broad range of IR wavelengths.[121] This satellite was used primarily by guest observers and produced interesting results in many areas.

Two small NASA IR satellites followed. The Submillimeter Wave Astronomy Satellite (SWAS), launched in 1998, uses radio techniques to observe molecules of astrophysical interest in the submillimeter region. The Wide-field Infrared Explorer (WIRE) was launched in 1999 to study the evolution of starburst galaxies—that is, galaxies forming new stars in large numbers—and to search for ultra-luminous galaxies and protogalaxies. However, a control problem that occurred just after launch prevented the acquisition of useful scientific data.

The program of relatively small satellites will be followed by SIRTF, the fourth Great Observatory, which is discussed below.

Radio Astronomy

Much of the radio region is easily observable from the ground, but the two ends of the region must be observed from space. The submillimeter and millimeter regions were discussed with the infrared region, to which they are an extension. At the other end of the window, the long-wave end, the ionosphere is opaque. At even longer wavelengths, interplanetary space is also opaque, but there is a region from about thirty to near 500 meters that can be observed from the vicinity of the Earth but not satisfactorily from the

[121] This range extended from 2.5 to 240 micrometers.

ground. A very difficult observation made from Tasmania, where the ionosphere tends to be thinner, and observations from several sounding rocket flights gave contradictory measurements of the spectral distribution of the radio background in this region.

In 1968 and 1973, NASA launched two essentially identical satellites to measure the spectrum more accurately. Called Radio Astronomy Explorers, the satellites each carried two, oppositely directed "rabbit-ear" antennas, each 225 meters from base to tip, in order to obtain at least modest angular resolution. The primary astronomical receiver covered the range from thirty three to 667 meters. Other receivers covered the range from thirty eight to 1500 meters. The longer wavelengths were primarily of interest for studying the ionosphere. The first flight successfully observed the terrestrial ionosphere and the major planets, but terrestrial radiation interfered with observations of the galaxy. Therefore, the second instrument was placed in orbit around the Moon, thus shielding the spacecraft from terrestrial radiation during the lunar occultation of the earth. Although these missions clarified the wavelength distribution of radio radiation from beyond the solar system, the results essentially agreed with predictions and otherwise provided little new information about this region. Obtaining more useful information will require higher angular resolution.[122] NASA is discussing in its long-range space science plans flying a low-frequency interferometer with a very long baseline.

As discussed above, Japan was responsible for launching a very productive radio mission, the Very Long Baseline Interferometry Space Observatory Program (VSOP). This spacecraft provided one element of a VLBI network. The various ground-based

[122] The maximum angular resolution of a telescope is inversely proportional to the wavelength of the radiation being collected. Specifically, the resolution in degrees is 70 times the wavelength divided by the diameter of the collector. Thus, even at 33 meters the resolution of each rabbit ear was only ten degrees. This meant that little could be learned of the detailed distribution of the radiation.

radio observatories that normally participate in VLBI measurements, including some in the United States, provided other elements. Since the separation of the satellite from the other observing sites was not limited by the diameter of the Earth, astronomers were able to obtain higher resolution images of sources than those previously available, such as of the nuclei of active galaxies.

General Relativity

Albert Einstein's General Theory of Relativity has proved successful for predicting the behavior of light and material bodies at scales ranging from those of atomic nuclei to galaxies but the differences between the predictions of the gravitational theories of Einstein and Isaac Newton are subtle. There are other theories of gravity that agree with Einstein's within the accuracy with which the effects can be measured currently. Experimental relativity is difficult on Earth because the large gravitational field of the Earth masks the small effects predicted by Einstein's and newer theories. The possibility of moving away from the earth into a different gravitation environment has interested physicists in several experiments.

The first test in space of the current theory arose as an operational rather than as a basic science problem. In order to predict the orbits of both the planets and of space probes sufficiently accurately to target the probes properly, relativistic corrections must be applied to the trajectories of both the probes and the solar system objects. The accuracy with which space probes can now be aimed continually confirms this aspect of Einstein's theory. Additional tests of Einstein's theory were provided by lunar laser measurements and planetary radar, as well as by dual frequency measurements of the delay of telemetry signals. Nevertheless, the General Theory of Relativity makes predictions that are not confirmed by these measurements.

Einstein predicted that a rapidly moving clock should run more slowly than a stationary clock. The flight of an atomic clock around the world in an airplane confirmed that a clock runs more slowly when moving at high velocity.[123] Einstein also predicted that a clock runs faster in a strong gravitational field than in a weak field. The gravitational field at 10.5 kilometers altitude is not enough weaker than that on the ground to confirm the predicted gravitational effect on clock rate. The desire to confirm the prediction more accurately led to Gravity Probe A, the first space experiment specifically designed to test the General Theory of Relativity. In 1976, Robert Vessot of SAO flew a hydrogen maser in a Scout rocket on a suborbital trajectory. The frequency of the clock at an altitude of 10,000 kilometers was compared accurately with the frequency of a similar clock on the ground. The frequency of the clock downlink was set so that the effects of the ionosphere on the different telemetry uplink and downlink frequencies could be removed. The sum of the delays of both the uplinked and downlinked signals canceled the large correction for the relative velocity of the probe and the ground. A correction also had to be made for the second-order Doppler effect, which depends on the square of the difference in the vector velocities of the two clocks. The experiment required very accurate tracking of the probe trajectory. When all necessary corrections were applied, the frequency change agreed with that predicted by General Relativity within an accuracy of seventy parts per million. The second-order red shift

[123] This phenomenon has also been confirmed by the fact that radioactive particles in cosmic rays decay more slowly than they do in a laboratory.

also matched the prediction of General Relativity. These results meaningfully constrain the degree to which competing theories can differ from Einstein's.

According to General Relativity, a gyroscope in a high-altitude satellite will change its pointing very slowly (by seven arcseconds per year) because it is moving in the curved space-time around the earth. In addition, there is a small effect on the pointing of the gyroscope (0.05 arcseconds per year) because the earth is rotating and, hence, drags its gravitational field with it. To measure these effects, William Fairbanks in 1964 proposed Gravity Probe B (GP-B). Although work was started nearly forty years ago, GP-B still had not flown at the time of this writing.[124] [III-18] This experiment contains two pairs of cryogenically cooled quartz gyroscopes, with the members of each pair pointing in orthogonal directions. The pointing of each gyroscope with respect to a star must be measured to within approximately one milli-arcsecond, equivalent to the angle subtended by a human hair at a distance of 16 kilometers. The absolute drift rate resulting from the relativity effects is ten million times smaller than that of the best Earth-bound gyroscopes. A small telescope accurately pointed to a bright star is to be tightly held relative to these gyroscopes. The gyroscopes and the telescope are cooled in an enclosure filled with liquid helium. These gyroscopes and the telescope are to be well shielded by an outer shell. The entire satellite will be stabilized to 0.1 arcseconds and flown in a polar orbit at 800 kilometers. A comparison of the readout of the two gyroscopes with the direction of the star can measure the frame dragging and curved field

[124] Along the way, there have been a number of technological advancements. One of particular importance to astronomy was the development of the porous plug. This allows the escape of helium gas, formed as liquid helium slowly warms but not the escape of the liquid helium itself. This type of plug has been used on all infrared astronomy satellites and probably made such satellites successful.

effect. After Fairbanks' death, his colleague, Francis Everitt, took over the development of the experiment.

The Great Observatories

By the early 1980s, NASA had four large astronomical spacecraft in various stages of development. Between them, they covered the wavelength regions from high-energy gamma rays to the short radio region. In order of decreasing wavelength, they were: the Gamma Ray Observatory (GRO, now the Compton Gamma Ray Observatory, CGRO), the Advanced X-ray Astrophysics Facility (AXAF, now Chandra), the Hubble Space Telescope, and the Space Infrared Telescope Facility (SIRTF, originally the Shuttle Infrared Telescope Facility).[125] NASA's Director of Astrophysics, Charles Pellerin, came up with idea of calling these spacecraft the "Great Observatories." The labeling was quite effective as a way of identifying the set of missions as an unique combination, and has been used since. [III-34]

The four Great Observatories shared various problems in their development. Each except CGRO took more than twenty years from the beginning of development until launch. Each was squeezed by financial restraints that both lengthened the program (and thus increased the total cost) and, except for SIRTF, caused descoping of the project. As each was planned for a Shuttle launch, each was affected, although in different ways, by the *Challenger* accident.

- *Hubble Space Telescope (HST)*

[125] SIRTF will measure wavelengths almost ten billion times longer than those CGRO measured.

The first of the Great Observatories to be launched was the HST.[126] Even before NASA was created, astronomers had dreamed seriously of a large space telescope.[127] [III-1] As early as 1962, a Space Studies Board summer study suggested that it was time to start planning of such an instrument.[128] This was an exciting possibility, and not only for the astronomers. NASA's Langley Research Center started a study of the project, with a human along as an observer. Several aerospace companies, partly funded by NASA, began studies of how such a telescope might be launched and controlled.[129] Aden Meinel, an early proponent of a large space telescope, started a Space Division at the Kitt Peak National Observatory even before the start of the Apollo program. He was a major proponent of the telescope at both the 1962 and 1965 SSB meetings.

Not all astronomers were enthusiastic about the project. To quote Meinel, "Ira Bowen [the director of the Mount Wilson and Palomar Observatories] said at one meeting that one could never stabilize a space telescope enough to yield high resolution. He said that simply pulling out the dark slide would disturb it. He also remarked that higher [angular] resolution wouldn't be of much importance to astrophysics."[130]

In spite of the strong division of opinion about a large space telescope, by the 1965 SSB summer study, momentum behind the project had grown to the point that NASA Headquarters decided that it was important to start planning for the mission.

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[126] For an outstanding history of HST, with special emphasis on the political complications the project had to navigate, see Robert W. Smith, *The Space Telescope: A Study of NASA, Science, Technology, and Politics* (New York, NY: Cambridge University Press, 1989).
[127] Lyman Spitzer, in Lyman Spitzer and Jeremiah P. Ostriker, eds., *Dreams, Stars, and Electrons*, p. 369, with reference to H. Oberth, Die Rakete zu den Planetenraumen (Munich, Germany: R. Oldenbourg-Verlag, 1923). Spitzer actually credited German rocket scientist Herman Oberth for suggesting a space telescope in 1923.
[128] Space Science Board, *A Review of Space Research* (Washington, DC: National Academy of Sciences, 1962).
[129] The Boeing Company, "A System Study of a Manned Orbital Telescope."
[130] Aden Meinel, personal communication.

Various additional studies were funded to prove the feasibility of the idea and to investigate the areas thought most likely to require extensive development. A committee of the SSB, under the chairmanship of Lyman Spitzer, began a four-year activity to define the scientific uses of a large space telescope.[131] The Astronomy Program in NASA Headquarters and astronomers on the Astronomy Working Group (an advisory committee that was composed of astronomers from both NASA centers and the non-NASA astronomy community) began to develop the arguments for such an instrument.

In 1970, NASA established two committees: an LST[132] Task Group to map out the engineering requirements of the project, and a Scientific Advisory Committee to define the scientific requirements. NASA Headquarters officials chaired both committees. The Task Group was primarily an in-house committee from NASA centers; the Advisory Group had a primarily, but not exclusively, non-NASA membership.

In 1971 and early 1972, Goddard Space Flight Center and Marshall Space Flight Center conducted competitive Phase A (preliminary) studies of the LST. However, when it came to deciding how to partition work between the centers, the decision was based primarily on the fact that Goddard already was fully involved with other science projects, while Marshall, whose work was declining after the push for Apollo, was anxious for a new responsibility. Hence, the overall management of the project was assigned to Marshall in 1972. Nevertheless, Goddard, with its experience in astronomy, retained the

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[131] Space Science Board, *Scientific Uses of the Large Space Telescope* (Washington, DC: National Academy of Sciences, 1969).

[132] Although LST stood for Large Space Telescope, in the minds of many astronomers it also stood for the Lyman Spitzer Telescope, given Spitzer's seminal role in proposing the concept.

management of the scientific instruments. At the urging of the scientific community, C. Robert O'Dell was brought to Marshall as the project scientist. Because Marshall would be managing the project, the Science Advisory Group was transferred to Marshall under O'Dell's leadership. Typical instruments were defined, and various groups were selected to work with the project to ensure that the spacecraft could accommodate such instruments. At about the same time, it was decided that the project should be divided into three sections: the Support Systems Module, the Optical Telescope Assembly, and the Scientific Instruments, each to be contracted for separately. This made the management of the project particularly complex.

In early 1973, politically astute NASA managers realized that the cost of the LST would limit their ability to sell it to either the Administration or Congress. Hence, Marshall was given a cost target well below its estimate of the cost of the telescope concept then under examination. Various cuts were made in the plans to reduce the cost; these reductions often had to be reinstated later in the program. The flight of a precursor 1.5-meter telescope to test the many complicated systems on the LST was dropped at this time.

In 1974, Congress appeared unenthusiastic about the LST. The House cut all funds for the project. At this point a few astronomers, primarily in Princeton, rallied their colleagues nationwide to lobby for the LST. A major argument made by skeptical Congressmen was that the National Academy of Science's study of astronomy in the 1970s barely mentioned the LST. This was partly the case because the study's chairman, Jesse Greenstein—perhaps because he had been burned almost three decades earlier by his V-2 experience and also because of his West-coast connections—was unenthusiastic about the large space telescope idea. More importantly, the study committee doubted that the telescope could be launched before 1980, thus falling outside the range of the committee's responsibility. By this time, the Academy had embarked on a new study that was to elevate the LST to top priority, but this study had not yet been completed. To counteract the impact of the Greenstein report, the study committee was again polled for its views on the LST. This time, after additional lobbying within the astronomical community, the Academy committee unanimously gave the LST top priority. Influenced by this result and extensive lobbying, the Senate was convinced to include the requested funding. As often happens, the House-Senate conference committee split the difference; NASA received half of the amount that had been requested.

Congress agreed to supply additional funds for the project only if significant foreign involvement in the LST was included; this would decrease the cost of the project to the United States. After extensive negotiations between NASA and the ESRO (later succeeded by ESA), Europe agreed to supply a major scientific instrument and the solar arrays. In return, European astronomers were guaranteed 15 percent of the observing time. [III-29] Although both the decision to accept a European instrument without competition and the guarantee of observing time upset some U.S. members of the study teams, it was likely that the Europeans could have successfully bid for fifteen per cent of the observing time in any open competition. Moreover, it was unlikely that NASA would have been able to fund an additional instrument, or even get Congressional approval for the LST overall without the European contribution.

In October 1975, President Gerald Ford cut the federal budget by $28 billion in order to try to balance the budget in three years. The NASA response to its share of the cut was to drop the new start for the LST in the Fiscal Year (FY) 1977 budget request. The Office of Management and Budget also felt that because of a slip in the Shuttle schedule, FY 1977 was too early to start LST, and James Fletcher, the Administrator of NASA, believed that the new start was politically unfeasible. Instead, NASA requested a new start for the Solar Maximum Mission in FY1977, and no funds specifically for the LST. Again the astronomical community launched a major lobbying effort, both in Congress and with NASA. The NASA administrator then argued for support of the LST with President Ford. The result was that a new start for the project slipped to FY 1978. The "L" was dropped in references to the project—making it just "ST"—so as not to advertise its cost, although some astronomers were concerned that the name change was an indication that the project's scope might be cut further. [III-24, III-25]

At about this time, Senator Proxmire asked NASA why the average American taxpayer should want to pay for such an expensive project. NASA's answer was that for the price of a night at the movies, the average American could enjoy fifteen years of exciting discoveries. Although it is unlikely that this response made any difference, it is interesting that as both the ST and movies have increased in cost, the statement is still approximately true.

NASA Headquarters directed the Marshall Space Flight Center find ways to cut the cost of the project in preparation for a FY 1978 new start. Marshall suggested various ways, of which the most draconian was to decrease the size of the telescope's mirror. The original plan called for a three-meter mirror. Both contractors and scientists were asked to look at the impact of including a mirror in each of three sizes: 3, 2.4, and 1.8 meters.

A major objective of the ST was to improve knowledge of the Hubble constant. This is the ratio between the speed of recession of a galaxy and its distance. The Milky Way is a member of a group of thirty to fifty galaxies that interact gravitationally. Thus their motions are affected by this gravitational interaction in addition to the expansion of the universe. To measure the Hubble constant, it is necessary to determine the distances of galaxies outside this Local Group. The most significant collection of the nearest such galaxies lie in the Virgo cluster. Thus, it had been assumed from the beginning that the LST must be able to observe Cepheid variable stars in the Virgo cluster. It had been known for most of a century that the period of the variation of a Cepheid is closely correlated with its intrinsic brightness. Hence, to measure its distance, it is only necessary to measure the period of the variation and the mean or maximum brightness. The astronomers determined that a 2.4-meter telescope could still obtain these measurements; a 1.8-meter telescope could not. Therefore the astronomers on the Science Advisory Group agreed that they could accept a 2.4-meter objective, but that they would recommend that the project be ended rather than settle for a 1.8-meter mirror. [III-23]

Also, facilities existed for the manufacture of a precise 2.4-meter mirror, while new facilities would have to be built for a three-meter mirror. This would greatly increase the cost of the Optical Telescope Assembly. Reducing the mirror size to 2.4 meters would also relax the pointing requirements and simplify the pointing and control system. Moreover, using a 2.4-meter mirror would simplify the control design even more by allowing the designers to wrap the heavy Support Systems Module around the telescope.

By the time the FY 1978 budget was ready to go to Congress, NASA had gotten both the President and the Office of Management and Budget enthusiastic about the project. Moreover, after several years of experience, the astronomers had become more skillful and sophisticated lobbyists.

A new start for the ST was approved at last in the President's FY 1978 budget proposal. [III-28] Technical problems now came to the fore. Because of stringent restrictions on overall NASA personnel as well as on the project's budget, and because Marshall had a reputation of excessively enlarging project personnel, Marshall was given a very stringent personnel cap for the telescope project. With far too few capable people, Marshall had to manage two associate contractors, an international partner, and another center, each of which was in turn dealing with a number of subcontractors. Partly for this reason and probably because of the reluctance of the national security community to allow "outsiders" full access to those portions of the project with a national security heritage, NASA was unable to monitor its contractors closely. Also, relations between Marshall and Goddard were severely strained for the first few years of the project.

Almost immediately after the Phase C/D (development, construction, and preparation for launch) contracts were awarded, each of the contractors increased their cost estimates substantially. Yet, Marshall was not allowed to budget for any additional funds. These factors led to a continuing series of severe problems until NASA Headquarters stepped in in a major way in 1983. Project managers were replaced at both Marshall and Goddard. The new managers made a determined effort to work together, thus solving one problem. Also, NASA Headquarters, after careful review of the project, agreed that substantially more money and manpower should be allotted. Although, as in any complex technological project, there were many problems after this, they were under more control. There were also schedule slips, but a launch in late 1986 still seemed possible. The 1986 *Challenger* accident eased the schedule problem, but also substantially increased the cost of the program as the spacecraft remained in storage in a clean room in Palo Alto, California, for three years, while the project team had to be kept together until the launch.

As the Ramsey Committee had stated in the 1960s, university astronomers wanted a non-NASA institute to manage the science of the project. In contrast, astronomers at NASA's Goddard center were anxious to have scientific control of the project. This led to a major fight, which the university-based astronomers won. [III-27] In addition to granting the wish of the scientific community, NASA Headquarters recognized that the size of the necessary institute would overwhelm Goddard, and particularly its small astronomical staff. The Space Telescope Science Institute (STScI) got off to a rocky start in its relations with NASA. Riccardo Giacconi, the director selected, had ambitious plans for the STScI, and immediately indicated that the staff had to grow significantly above that described in the proposal. Just as NASA Headquarters officials had failed to respond to the sometimes desperate requests for funds from Marshall, they also tried to squelch the staffing and budget growth demanded by the STScI. Finally, after a careful look at the functions for which NASA believed the STScI should be responsible, some of which had not been included in the original specifications, NASA agreed to a major increase in personnel and space. Over time, the relations between Giacconi and NASA became smoother, with each developing a better understanding of the other's problems.

The STScI maintains an archive not only of HST observations but also of UV observations from other satellites, particularly the IUE. Rather than depending on the observer to produce reduced data from the HST, the STScI archives the raw data and calibrates these “on the fly” when they are requested from the archive. This procedure removes any delay (beyond an agreed proprietary period) in making the data available to other astronomers. This archive has been quite successful, attracting many users and resulting in a number of scientific papers.

There was great delight among astronomers in April 1990 when the space telescope was finally launched. By then it had been named the Hubble Space Telescope after Edwin Hubble, the astronomer who first demonstrated that the more distant a galaxy, the higher is its velocity of recession. A little later, the joy turned to dismay when it was discovered that the images were not of the expected quality. Analysis showed that the telescope was suffering from spherical aberration. Even if a backup mirror had been completed (work on it was stopped to save money), it would have been impossible to exchange mirrors in orbit. Return of the telescope to the ground had been ruled out earlier because of the cost, the danger of contamination, and the possibility of damage to the telescope from re-entry and landing. Therefore, an intensive period of study ensued, led by the STScI but including NASA and other optics experts, to determine the most effective remedy. [III-37] The individual instruments could have been redesigned to correct the problem but, because of the financial problems, no backup instruments were available except for the Wide Field/Planetary Camera (WF/PC).

Finally, it was realized that the backup WF/PC could be easily corrected and that a single system could be designed to correct the image for each of the other instruments.

The problem was how to install such a system with stringent alignment requirements in a tight space. While taking a shower in Germany, Jim Crocker, a HST engineer, was inspired by the showerhead to create a mechanical design that could meet the restrictions. To add the correction system, called the Corrective Optics Space Telescope Axial Replacement (COSTAR), it was necessary to remove one of the original instruments. The High Speed Photometer was selected for removal. As this instrument's principal investigator remarked to the author some years later, "What wonderful results we could have obtained with the improved image quality!" Three years passed before the new instruments could be completed and a shuttle repair mission could be launched. [III-38] In the meantime, mathematical methods were developed to get reasonable images from the HST, but they did not work well for extended sources or crowded regions. Also, the poor light concentration in the image limited the faintness that could be reached.

The remarkable images obtained after the corrective optics were installed vindicated the hopes of astronomers who had worked so hard for large, diffraction-limited optics in a satellite that could point sufficiently accurately to avoid degrading the image. The problem of improving the determination of the Hubble constant started as soon as possible after the correction of the optics problem. The results to date are still somewhat controversial, but most astronomers believe that that the constant is now known within ten per cent, in contrast to the fifty per cent uncertainty before the HST observations. An impressive and surprisingly fruitful observation entailed keeping the telescope pointed continuously to the same "uninteresting" place for ten days. In the resulting image, sources were detected which are as faint as 1/10,000,000,000 of the brightness of the faintest star normally visible to the human eye in a clear, dark sky.

Some of the galaxies (There were very few individual stars in this tiny field) are so far away that their light left them when the universe was only a few per cent of its present age. These images not only show that galaxies formed very early in the history of the universe, but that most are somewhat different from the modern galaxies near the Milky Way. The ability to resolve small details near the centers of active galaxies has established almost beyond any doubt that these centers contain black holes. Images and spectra of objects ranging from comets and planets to very distant galaxies have impacted modern astronomy (and the public's perception of the cosmos) as much as Galileo's telescope did more than three centuries earlier.

- *Compton Gamma Ray Observatory(CGRO)*

The second Great Observatory was CGRO, launched in 1991. It was named at launch to honor physicist Arthur Holly Compton, who had studied the behavior of gamma rays. This spacecraft also had a somewhat tortuous history.[133] Originally, a somewhat smaller version of CGRO's Energetic Gamma Ray Experiment (EGRET) was proposed for the HEAO program, but as a result of cost overruns on the Mars Viking project, three large experiments, including EGRET, were removed from the HEAO program. EGRET was then studied as an independent Explorer mission, with the spacecraft to be built by the Johns Hopkins Applied Physics Laboratory (that had built the SASs). A year later, NASA Headquarters decreed that the Multi-Mission Spacecraft (MMS) should be used, but that in turn proved to be so expensive that the mission was

[133] Aside from the advantage of not being the first, CGRO benefited from involving only a single center in the management (although instruments came from other institutions). In addition, it did not have to deal with national security problems.

cancelled. By this time, 1976, it was realized that other gamma-ray experiments were also important, and the concept of a multi-experiment gamma ray mission, designated the Gamma Ray Observatory (GRO) was developed. After some study and an announcement of opportunity, five experiments were selected in 1978.

By 1981, it appeared that a spacecraft with these five experiments would be too large and too heavy. The Gamma-Ray Line Experiment was therefore dropped. [III-32] This was one of the same experiments that had previously been dropped from HEAO. As all of the Space Shuttle programs were significantly delayed by the *Challenger* accident, the GRO launch date was reset for around 1990. There were of course additional costs due to the launch delay. The final launch date was slipped again, this time to 1991. An attempt made to develop an optimum technical and budgetary schedule led to the GRO being ready about nine months before it was actually possible to launch it. (Probably the last year of the delay resulted from the desire to launch the HST first.)

Four instruments were carried on the final spacecraft.[134] The Burst and Transient Source Experiment (BATSE) was composed of eight gamma-ray modules placed on the spacecraft to provide all-sky coverage.[135] Not long after launch, the tape recorder on CGRO failed, thus necessitating real-time data transmission. This proved to be a great advantage, as it allowed the information about a burst detection to reach the ground within seconds rather than in the two hours that had been planned.[136] The Oscillating

[134] Together, the instruments covered the energy range from below 0.1 to about 3 x 10^4 MeV.

[135] Each module contains two detectors, one designed for high sensitivity and the other for higher energy resolution. They can measure gamma-ray temporal variations on time scales down to several microseconds and energy spectra in the range 30 keV to 1.9 MeV.

[136] The decision not to depend much on shuttle servicing turned out to be a blessing. Both tape recorders started to give trouble after about six months and failed completely after the first year. In order to get real-time data from the satellite, NASA added a Tracking and Data Relay Satellite System (TDRSS) receiving station in Australia, thus closing the previous gap in satellite coverage. This continual real-time receipt of data from the satellite permitted prompt alerts to gamma-ray bursts.

Scintillation Spectrometer (OSSE) covered the low energy range.[137] The Compton Telescope (COMPTEL) was based on Compton scattering.[138] This instrument detected both the energy and the direction of the gamma ray. EGRET covered the high-energy range.[139] This was a much larger version of the SAS-2 spark chamber with the addition of good energy measurement. The accuracy to which a point source could be located varied from five arcminutes for strong sources to forty-five arcminutes for the weakest sources.

The CGRO was originally designed to be serviced by the shuttle and returned to the ground for repair. The changes in the shuttle program after the *Challenger* accident increased the cost of launches sufficiently that this was no longer cost-effective. The degree to which the spacecraft could be refurbished in orbit was also reduced to save money. By 2000, several of CGRO's gyros had failed. NASA was concerned that if another failed, the spacecraft would be uncontrollable and could re-enter Earth's atmosphere and drop heavy pieces in a populated area, causing damage and, possibly, loss of life. The gyros could not be serviced individually in-orbit, but the entire unit could have been replaced. This was considered to be too expensive, and recapture was considered dangerous as well. Therefore, though it was still producing excellent science,

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[137] The range of OSSE was 0.1 to 10 MeV. A phoswitch system was used with cesium iodide crystals behind sodium iodide crystals. The field of view was limited to 3.8 by 11.4 degrees by a tungsten alloy shield.

[138] COMPTEL detected gamma rays by the occurrence of two successive interactions: first a Compton scatter collision occurred in a detector of material with low atomic number; then a second interaction took place in a lower plane of material of high atomic number in which, ideally, the scattered gamma ray was totally absorbed. Gamma rays below about 2 MeV cannot be detected; the upper limit to the energy for which neutrons can be discriminated from gamma rays is about 100 MeV.

[139] EGRET covers the region above 20 MeV.

the spacecraft was commanded in 2000 to reenter the atmosphere. It burned up over the Pacific Ocean.

CGRO was exceedingly productive in areas of study ranging from the solar system to distant regions of the universe. Fichtel and Trombka list the following accomplishments:

1. the finding of new objects including high-energy, gamma ray blazars (a kind of active galaxy)
2. a very clear separation of the gamma-ray properties of blazars and Seyferts
3. a major increase in knowledge of gamma-ray bursts
4. the observation of an increased fraction of the pulsar electromagnetic radiation being emitted as gamma rays as pulsars ages up to one million years, and the detailed knowledge of their spectra
5. the determination with high certainty that cosmic rays are galactic
6. the detailed mapping of the galactic diffuse radiation, including the aluminum line and the measurement of the pi meson bump in the high-energy gamma-ray spectrum
7. the detection of gamma-ray lines from SN1987A[140] and Cas (Cassiopeia) A
8. the absence of microsecond bursts and its implication for certain unification theories
9. the existence of energetic particles near the sun for over ten hours following a flare and the associated implication for the shock acceleration theory, and
10. the measurement of the spectrum of the diffuse, presumably extragalactic, gamma radiation with a flat spectrum in the high-energy region consistent with a blazar origin.[141]

- *Advanced X-ray Astrophysics Facility/Chandra X-ray Observatory*

The third of the Great Observatories, Chandra, was a follow-on to HEAO-2, *Einstein*. Like *Einstein*, but much larger, it carries grazing incidence mirrors with

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[140] SN1987A is the supernova that occurred in 1987 in the nearby galaxy, the Large Magellanic Cloud.
[141] Fichtel and Trombka, *Gamma-Ray Astrophysics: New Insight into the Universe*. The information on the CGRO instruments is also from this book.

excellent image quality. With a focal length of ten meters, the spacecraft can detect point sources more than twenty times fainter than previous X-ray telescopes and provides eight times better angular resolution.

AXAF started in 1976 with a proposal from Giacconi and SAO's Harvey Tannebaum.[142] [III-26] After a competition among NASA centers, the project was assigned to Marshall in 1977. There were originally two spectrometers on AXAF. A Bragg crystal spectrometer from MIT's Claude Canizares was at the focal plane of the telescope. A calorimeter from Stephen Holt of Goddard was also included. The Bragg instrument was dropped in 1989 to save money. Originally plans were to launch the spacecraft into a low orbit from which the shuttle could service it. Because of the severe increase in shuttle launch costs after the *Challenger* explosion, this no longer seemed feasible. Eliminating this possibility saved substantial money, including both servicing costs and additions in spacecraft construction. Instead, project officials decided to launch AXAF into a high orbit where the spacecraft would be less affected by the Earth's radiation belts. The combined weight of the spacecraft and the additional rocket stage needed to reach the desired high orbit from shuttle altitude turned out to be too heavy for a shuttle launch. Two significant changes were made to the spacecraft to reduce the weight: the calorimeter was dropped and the number of mirrors was decreased from six to four. The higher observing efficiency in the new orbit compensated for the decrease in the total mirror area. Plans were to fly the calorimeter on a separate spacecraft; that

[142] Smithsonian Astrophysical Observatory, "Proposal to NASA for the Study of the 1.2-Meter X-ray Telescope National Space Observatory," April 1976.

spacecraft was cancelled in 1993, again because of funding constraints. Instead, the calorimeter was put on the Japanese satellite Astro-E, which failed. [III-39]

AXAF, like the GRO, had to wait for the HST launch, which was delayed by the *Challenger* accident. Spacecraft integration proved to be more difficult than anticipated and there were some problems with components. These technical problems benefitted from the launch delay.

Launched in 1999 (and renamed Chandra after astronomer Subrahmanyan Chandrasekhar) , AXAF/Chandra had a productive first year observing objects from comets to quasars. It discovered that the X-rays that had been observed previously from comets were a result of the collision of the solar wind with ions in the comet. A flare was observed from a brown dwarf, a star-like body that is too light to fuse hydrogen for energy. The observatory has observed two galaxies merging.[143] Many galaxies are extremely bright in the X-ray region but optically faint. There are many low-luminosity black holes that are not understood. As Chandra Project Scientist Martin Weisskopf remarked, “Every image leads to a discovery.”

- *Space Infrared Telescope Facility (SIRTF)*

The fourth, not yet launched, Great Observatory is the SIRTF. SIRTF will carry an 85-centimeter telescope that will be cooled to 1.6 K. To cover the broad wavelength range and provide both imaging and spectroscopy, SIRTF will carry three focal-plane instruments.[144] The Infrared Array Camera will use large area, two-dimensional IR array

[143] NASA Marshall Space Flight Center press release, August 22, 2000.
[144] The Multiband Imaging Photometer (MIPS) for SIRTF will provide background-limited imaging and photometry in the range from 30 to 200 micrometers and a low resolution spectrometer for spectral energy distributions. It will also use an array detector to provide broad band photometry and mapping from 200 to

detectors to provide diffraction-limited angular resolution in the nearer IR.[145] The IR Spectrometer will cover the entire range of wavelengths in which SIRTF will be used, with a variety of resolutions and modes.[146] The Multi-band Imaging Photometer will provide both imaging and low-resolution spectrometry in the mid- and far IR.

SIRTF was originally called the Shuttle Infrared Satellite Facility. The plans were to keep the spacecraft attached to the shuttle or at least in the shuttle's vicinity and to return it to Earth at the end of the shuttle's mission. By 1983, IRAS had shown that a long-lived IR satellite was feasible. Also, there was some concern that material around the shuttle might cause problems. The name of the mission was therefore changed to the Space Infrared Telescope Facility, and it was decided to fly the spacecraft in a 900-kilometer orbit, above the strongest radiation belts. In 1989, the planned orbit was raised to a 100,000-kilometer orbit and later to a heliocentric, Earth-trailing orbit. This change will improve both scientific performance, because of the lower background in the far IR, and observing efficiency, as the Earth becomes a small target. The move to a heliocentric orbit was accompanied and somewhat enabled by decreases in payload complexity.

Both the SIRTF schedule and the spacecraft, instrument, and mission design were severely delayed by funding constraints. However, as Project Scientist Michael Werner noted: "The long delay allowed us to invest in enabling technology—detector arrays, cryogenic technology, and lightweight optics—and the tough funding encouraged very creative thinking on the part of the scientists and the engineers. As a result, the $500

700 micrometers with a possible extension to 1.2 millimeters. The Infrared Spectrograph (IRS) consists of several long-slit and echelle-mode spectrographs covering the interval from 2.5 to 200 micrometers. Resolving power will vary from 100 to 2000. Its large collecting area and sensitive array detectors will provide sufficient capability to observe many different types of sources. Finally, the Infrared Array Camera (IRAC) will map large fields using a step-and-stare method, at 3.6, 4.5, 5.8, and 8.0 micrometers.

[145] The telescope will provide diffraction-limited images from 2 to 27 micrometers.

[146] The instrument will cover the energy range between 2.5 and 200 micrometers.

million SIRTF we now have has almost the same mirror size, the same lifetime, and the same basic instrument functionality as did the $2 billion-plus version talked about in 1990." The project got back on track after a long launch delay by a combination of ingenuity and technology advances, plus the fact that it became an example of NASA's 1990's "faster, better, cheaper" approach to mission development and operations.

The Future

With the launch of SIRTF, planned for late 2001, every region of the electromagnetic spectrum not observable from the ground, with the exception of long-wave radio radiation, will have been surveyed and observed with good sensitivity and angular resolution. It is probable that most types of celestial sources will have been identified, although there will certainly be surprises. Indeed, many cosmological phenomena are not yet completely understood. A test of Einstein's theory of relativity will have been conducted successfully and another will be far along in development.

Plans for the next decade are ambitious. [III-40] They include small missions dedicated to answering specific questions, and very complex missions aimed at increasing angular resolution, always a major *desiderata* in astronomy. The increase in resolution will permit detailed study of crowded sources, such as the vicinities of black holes in galactic centers. Improved resolution will also allow for the comparison of galaxies as they existed early in the life of the universe with those near the sun that we see now, some thirteen billion years later.

The smaller missions are an extension of the Explorer program, a program of small scientific satellites started early in the NASA program, with several important changes. The most critical is that the new program includes three mission classes (mid-sized, small, and university class), each with a strict funding cap. In addition, there is a fourth class for participation in non-NASA missions, also with a strict funding cap.

FUSE was the first mission within this new scheme (although it started at least twenty years ago as a much more ambitious project). At least four missions per year, with a total funding cap of $226 million are planned. Included in the cap are the costs of project definition, development, launch service, mission operations, and data analysis. A major problem in the past has been that when a mission was accepted, no detailed design study had been conducted. Hence, the proposed costs were highly uncertain and were often greatly exceeded by the final cost. A new approach is to select missions tentatively, with final selection after a period of design study sufficient to provide a meaningful estimate of costs. If the costs, including contingencies, exceed the cap, the mission will be stopped or descoped. A third change is that the proposing institution will be given more responsibility for many of these missions. An example of the largest new Explorer missions is Swift, which will monitor the sky for gamma-ray bursts. When one is discovered, it can start X-ray and optical observations of the site within fifty seconds and send initial coordinates of the burst to the ground within fifteen seconds. In this way, scientists should get much important information on the nature and origin of such bursts.

The complex missions are ambitious indeed. They are a new generation of "Great Observatories," going beyond the capabilities of the earlier ones with high sensitivity as well as high angular resolution. Again, they have a number of characteristics in common. All are much larger and have greater collecting area than the preceding generation of instruments. Because of their size, most must be launched in a collapsed configuration and assembled automatically in orbit. Most are based on interferometry in order to combine information from independent instruments. Interferometry has been used on the ground by radio astronomers for many years but has been used successfully in the optical region only in the past decade. Although interferometry will be far from trivial even in the IR region, it will be exceedingly difficult at high energies, as the relative positions of the component telescopes must be known to a small fraction of a wavelength. All of these missions will be expensive enough, as well as capable enough, so that international cooperation is imperative. Finally, most if not all of the observing time will be open to all astronomers in a guest observer mode. That is, each will be an international facility.

In addition to the technical challenges presented by the hardware, data handling from these large missions will be a major problem. Data handling involves not just collecting and transmitting the data, but also producing well calibrated data in a form that can be used by someone familiar with astronomical observation generally but not familiar with the quirks of a particular instrument. Interferometry involves much more data and more complicated data processing than do single telescope techniques. Finally, many of these instruments will be placed near the L2 point to avoid both the occultation of a large portion of the sky by the Earth and the Earth's radiation environment.

An example of one of these missions is the Terrestrial Planet Finder. For this mission, two or more medium-sized near-IR telescopes will be linked interferometrically to provide sufficient angular resolution to separate a medium-sized planet from its parent star and to observe it spectroscopically. At present, only much larger planets can be detected by their gravitational influence on their parent stars or, in special orientations, by planetary eclipses. In the portion of the radio region that can be observed from the ground, a satellite in orbit will be linked with ground-based instruments to provide baselines several times longer than the diameter of the Earth. In the longer wavelengths, antennas and receivers very widely spaced in orbit will provide significant angular resolution for the first time. To detect gravity waves longer than those observable from the ground, a pair of satellites whose separations are accurately measured will look for tiny changes in the separation as a result of the passage of the wave.

The possible future of space-based astronomy and astrophysics is thus both exciting and daunting.

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