 ond stage eliminated all random failures, since the circumstances of this mishap required a failure to have occurred during the specific 14-minute period (ten minutes during which the transmitters were off, plus four minutes of tube warm-up time) without teleme- try. The third stage consisted of identifying the subset of single failures from the second stage that could lead to extended loss (hours to days) of downlink. The fourth stage was focused on the subset of the third-stage failures [B-4] that could be correlated with the Pressurization Sequence, which included several commands and activities that were being executed for the first time during the mission. Those failures that survived through the fourth stage were then examined with respect to supporting test data, analyses and failure history. Specific tests and analyses were identified and performed to validate or invalidate postulated scenarios. This process permitted the Board to classify the failures as to the most probable cause and potential causes. As a result of these studies, analyses and tests, the Board was led to three principal conclusions: . First Principal Conclusion Despite extensive analysis of the circumstances surrounding the mission failure of the Mars Observer spacecraft, the Board was unable to find clear and conclusive evidence pointing to a particular scenario as the “smoking gun.” Most of the failure scenarios were determined to be implausible or extremely unlikely. The Board was, however, unable to eliminate several failure scenarios. From these remaining scenarios, the Board concluded through a process of elimination that the most probable cause of the loss of downlink from the Mars Observer was a massive failure of the pressurization side of the propulsion system. The Board also concluded that the most probable cause of that failure was the unintended mixing of nitrogen tetroxide (NTO) and monomethyl hydrazine (MMH) in the titanium tubing on the pressurization side of the propulsion system. This mixing was believed by the Board to have been enabled by significant NTO migration through check valves during the eleven-month cruise phase from Earth to Mars. This conclusion is sup- ported (but not proven) by NTO transport-rate data acquired by JPL, by NTO/MMH reac- tion simulations performed by NRL, and by NTO/MMH mixing tests performed by AFPL. Second Principal Conclusion The Board concluded that the Mars Observer spacecraft design is generally sound. The investigation did, however, identify issues (some unrelated to this failure) that should be addressed and corrected prior to any flight of the same or derivative-design spacecraft. [B-5] Third Principal Conclusion The Board concluded that, although the result was a very capable spacecraft, the orga- nization and procedural “system” that developed Mars Observer failed in several areas. In particular, the system failed to react properly to a program that had changed radically from the program that was originally envisioned. Too much reliance was placed on the heritage of spacecraft hardware, software, and procedures, especially since the Mars Observer mission was fundamentally different from the missions of the satellites from which the heritage was derived. The complementary strengths of JPL and Martin Marietta

EXPLORING THE UNKNOWN 473 Astro Space (formerly RCA Astro-Electronics and General Electric Astro-Space Division) were not used by NASA as effectively as they should have been. Secondary Conclusions In addition to its assessment of the most probable failure presented earlier, the Board found that the following failures must also be considered as potential causes of the loss of downlink: Electrical Power System failure resulting from a regulated power bus short circuit. Regulator failure resulting in NTO and/or MMH tank over-pressurization and rupture. Ejection of a NASA Standard Initiator at high velocity from a pyro valve, punc- turing the MMH tank or causing severe damage to some other spacecraft system. The Board was generally impressed with the spacecraft that was developed for the Mars Observer mission. However, considering the potential for reflight of an identical spacecraft, or the use of derivative designs or hardware in spacecraft currently in devel- opment or planned for future similar mission requirements, a number of specific con- cerns were noted: [B-6] Propulsion System Inappropriate isolation mechanisms between fuel and oxidizer for an inter- planetary mission. Lack of post-assembly procedures for verifying cleanliness and proper func- tioning of the propellant pressurization system. Current lack of understanding of the differences in pyro-initiator character- istics between European Space Agency initiators and NASA Standard Initiators. Inadequate thermal instrumentation, control, and modeling for the mission profile. Electrical Power System Potential power bus short circuit susceptibility, due to improper assembly, sin- gle component failure, or insulation failure. Command and Data Handling System Critical redundancy control functions can be disabled by a single part failure or logic upset. Redundant crystal oscillator (RXO) can lose one of its two outputs without remedy of fault protection. The actual state of the backup oscillator in the RXO is not available in telemetry. Software/Fault Protection A top-down audit of fault protection requirements, implementation, and val- idation is needed.

 Systems Engineering/Flight Rules The flight system should be qualified and capable of providing insight into critical mission events. An example of this would be the availability of teleme- try during critical events. The flight system should be allowed to maintain attitude control during crit- ical operations. If any rebuild or modification of the spacecraft is anticipated, the documen- tation should be updated to reflect the as-built/as-flown configuration. The Board noted that the Mars Observer that was built departed significantly from the guiding principles originally established for the program, yet the acquisition and management strategy remained unchanged. The role of JPL in this fixed-price procurement was, at best, cum- bersome, and did not appear to make the most effective use of the unique resource represent- ed [B-7] by JPL. In any event, the use of a firm, fixed-price contract was inappropriate to the effort as it finally evolved. The original philosophy of minor modifications to a commercial pro- duction-line spacecraft was retained throughout the program. The result was reliance on design and component heritage qualification that was inappropriate for the mission. Examples of this reliance were the failure to qualify the traveling wave tube amplifiers for pyro firing shock; the design of the propulsion system; and the use of a fault-management software package that was not fully understood. The Board also noted that the discipline and documentation culture asso- ciated with, and appropriate for, commercial production-line spacecraft is basically incompati- ble with the discipline and documentation required for a one-of-a-kind spacecraft designed for a complex mission. Mars Observer was not a production-line spacecraft. While the Board can find no direct linkage between the mishap and these systemic weaknesses observed in the Mars Observer program as it evolved over the years, these weaknesses, nevertheless, remain a significant concern for future programs. The Board would like to express its appreciation for the support provided to the inves- tigation by the six technical teams, the other NRL and AFPL personnel who supported it, the NASA representatives, the JPL Project Team and Investigation Board, and the MMAS Technical Teams. Document II-41 Document title: Office of Space Science, NASA, “Final Environmental Impact Statement for the Cassini Mission," June 1995. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Document II-42 Document title: Office of Space Science, NASA, “Supplemental Environmental Impact Statement for the Cassini Mission," June 1997.

EXPLORING THE UNKNOWN 475 Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. In compliance with the National Environmental Policy Act, NASA must issue an Environmental Impact Statement for every spacecraft launch it conducts. Inner solar system probes, whose systems operate using solar power, generally have been approved readily. Spacecraft that travel greater dis- tances, however, cannot depend on the sun but instead use radioactive materials for power. Such mis- sions have been the focus of substantial public opposition before launch due to fear that a launch failure of a spacecraft containing radioactive materials could devastate the environment and life on Earth. These documents contain NASA's analysis of the potential effects on Earth of a catastrophe involving the plutonium-laden Cassini spacecraft during either launch or passage by Earth en route to its final destination, Saturn. The low probabilities of devastating consequences allowed the launch to proceed, despite intense public protests. [cover page] Document II-41 Final Environmental Impact Statement for the Cassini Mission Solar System Exploration Division Office of Space Science National Aeronautics and Space Administration Washington, DC 20546 June 1995 [v] EXECUTIVE SUMMARY This Final Environmental Impact Statement (FEIS) has been prepared in accordance with the National Environmental Policy Act of 1969 (NEPA) (42 U.S.C. 4321 et seq.), as amended; the Council on Environmental Quality Regulations for Implementing the Procedural Provisions of NEPA (40 CFR Parts 1500-1508); and the National Aeronautics and Space Administration's (NASA) policy and regulations (14 CFR Subpart 1216.3) to support the decision-making process concerning the Proposed Action and alternatives for NASA's Cassini space exploration mission. PURPOSE AND NEED FOR THE ACTION The Cassini mission is an international cooperative effort being planned by NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI) to explore the planet Saturn and its environment. The mission would involve a 4-year tour of Saturn, its atmos- phere, moons, rings, and magnetosphere by the Cassini spacecraft, which consists of the

 Orbiter and the detachable Huygens Probe. The Huygens Probe would be released from the Cassini Orbiter to descend by parachute through the atmosphere of Saturn's largest moon, Titan. During the descent, instruments on the Probe would directly sample the atmosphere and determine its composition. The Probe would also gather data on Titan's landscape. The Cassini spacecraft would carry three radioisotope thermoelectric generators (RTGS) that use the heat from the decay of plutonium (Pu-238) dioxide fuel to generate electric power for the spacecraft and its instruments. The spacecraft would use radioisotope heater units (RHUS) (157 are planned), also containing plutonium dioxide, to generate heat for controlling the thermal environment onboard the spacecraft and several of its instruments. The U.S. Department of Energy (DOE) would supply the RTGS and RHUS to NASA. NASA would provide the ground communications network and two scientific instru- ments for the Huygens Probe. ESA would provide the Huygens Probe, and ASI would pro- vide major elements of the Cassini Orbiter's communications equipment and elements of several science instruments. The Cassini mission is part of NASA's program for exploration of the solar system. The goal of the program is to understand the birth and evolution of the solar system. Initially, this program concentrated on flyby or reconnaissance-type missions to the outer solar system. With the launch of the Galileo spacecraft in 1989, the program began its transition to exploration-type missions to the outer planets using orbiters and atmos- pheric probes. The Cassini spacecraft would make remote and close-up measurements of Saturn, its atmosphere, moons, rings, and magnetosphere. This information could also provide significant insights into the formation of the solar system and the conditions that led to life on Earth. [vi] ALTERNATIVES EVALUATED The Proposed Action addressed by this FEIS consists of preparing for and implement- ing the Cassini mission to Saturn to conduct a 4-year scientific exploration of the planet, its atmosphere, moons, rings, and magnetosphere. NASA proposes to launch the spacecraft from Cape Canaveral Air Station (CCAS) (formerly Cape Canaveral Air Force Station [CCAFS]) in October 1997 using a Titan IV (Solid Rocket Motor Upgrade [SRMU]) and a Centaur upper stage (i.e., Titan IV (SRMU)/Centaur) to place the Cassini spacecraft into a 6.7-year Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) trajectory to Saturn. The SRMU is the most recent upgrade of the solid rocket motor [SRM] used on the Titan IV. If the October 1997 launch opportunity were missed, a secondary launch opportunity exists in December 1997 using an 8.8-year Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory and a backup launch opportunity exists in March 1999 using a 9.8-year VEEGA trajectory. In the event that the Titan IV (SRMU)/Centaur were not available, a Titan IV (SRM)/Centaur would be used. The launch opportunities would remain the same. The alternatives to the Proposed Action evaluated in detail are a 1999 mission alter- native, a 2001 mission alternative, and the No-Action alternative (i.e., the cancellation of the mission). The 1999 mission alternative would entail dual Shuttle launches from the Kennedy Space Center (KSC), separated by 21 to 51 days, to deliver the Cassini spacecraft and the upper stages) into low Earth orbit. An on-orbit mating of the upper stage(s) and the spacecraft would be performed by astronauts followed by insertion of the spacecraft

EXPLORING THE UNKNOWN 477 in March 1999 into its 9.8-year VEEGA interplanetary trajectory to Saturn. A backup launch opportunity, a 9.4-year VEEGA, occurs in August 2000. The 2001 mission alterna- tive would use the Titan IV (SRMU)/Centaur to launch the Cassini spacecraft into a 10.3- year Venus-Venus-Venus-Gravity-Assist (VVVGA) trajectory to Saturn. The spacecraft would require 20 percent additional propellant, as well as completing development of and flight testing a high performance rhenium engine for spacecraft propulsion to accom- modate the amount of maneuvering associated with the VVVGA trajectory. An 11.4-year VEEGA backup launch opportunity occurs in May 2002. The No-Action alternative would cancel the mission. In developing the alternatives (i.e., the Proposed Action and the 1999 and 2001 mis- sions), the available options for the following key components of the mission design were evaluated: launch vehicles, interplanetary trajectories, and power sources for spacecraft electrical needs. Several criteria were used to evaluate the options: technological feasibility and avail- ability of the option for implementing the mission at the earliest opportunity, impact of the option on the ability of the spacecraft to achieve the mission science objectives, and potential of the option for reducing or eliminating environmental impacts that could be associated with the mission. The evaluation provided the following results: (1) the Titan IV (SRMU)/Centaur is the most capable U.S. launch vehicle available to implement the mission; (2) the Cassini mission to Saturn requires planetary gravity-assist trajectories; and (3) the spacecraft requires the use of RTGs to satisfy the mission electrical power needs. [vii] The overall result of the options evaluated indicates that implementation of the Proposed Action, with its three launch opportunities (i.e., primary in October 1997, sec- ondary in December 1997, or backup in March 1999), provides the greatest opportunity to achieve the mission science objectives. The 1999 mission alternative and the 2001 mis- sion alternative also are technically feasible and provide opportunities to achieve most of the science objectives planned for the mission but with less science return (i.e., data). ENVIRONMENTAL IMPACTS The only expected environmental impacts of the Proposed Action, as well as the 1999 and 2001 mission alternatives, would be associated with the normal launch of the Cassini spacecraft on the Titan IV (SRMU or SRM)/Centaur or the Shuttle. These impacts have been addressed in previous NEPA documents prepared by the U.S. Air Force (USAF) for its Titan IV launch operations at the CCAS (USAF 1986, USAF 1988a, USAF 1988b) and for the Titan IV using the SRMU (USAF 1990) and prepared by NASA for the Shuttle launches (NASA 1978, NASA 1979, NASA 1988b, NASA 1989b, NASA 1990). The evalua- tion of these alternatives also used other NEPA-related documentation, including the EIS for the Kennedy Space Center (KSC) (NASA 1979) and the KSC Environmental Resources Document (NASA 1994). For the Proposed Action, the environmental impacts of a normal launch of the Cassini spacecraft on a Titan IV (SRMU or SRM)/Centaur would result from exhaust emissions (i.e., the exhaust cloud) from the two solid rocket motors (principally aluminum oxide par- ticulates [A1203], hydrogen chloride [HC1], and carbon monoxide (CO]), which would have a short-term impact on air quality in the vicinity of the launch site; noise from the

 SRMUS or SRMs, which would not adversely impact the nearest unprotected person for the general public); deposition of acidic SRMU or SRM exhaust products, largely on the launch complex itself, but which could reach nearby marsh and surface water areas where natural buffering would substantially reduce any impacts; and short-term impacts on stratospheric ozone along the launch vehicle's flight path from the SRMU or SRM exhaust products. No substantial long-term environmental impacts would be associated with a nor- mal launch of the Cassini spacecraft for any of the launch opportunities. The radiological concern associated with the mission is the potential release of some of the approximately 32 kg (71 lb) of plutonium dioxide (consisting of around 71 percent by weight Pu-238 at launch) in the RTGS and RHUS onboard the spacecraft. In the unlike- ly event that an accident were to occur during the launch of the spacecraft (i.e., from the time of ignition of the SRMUS or SRMs, through the insertion of the spacecraft into its interplanetary trajectory), the safety features incorporated into the RTGS and RHUS, in most cases, would limit or prevent any release of the plutonium dioxide fuel. However, in the unlikely event of a launch phase accident causing a release of plutonium dioxide fuel, no health effects (i.e., excess latent cancer fatalities [above the normally observed cancer fatalities]) would be expected to occur if members of the population were exposed to the released radioactive fuel. For launch Phases 1 through 6 on the Titan IV (SRMU)/Centaur, four accident sce- narios were identified as representative of the categories of failures that could release [viii] plutonium dioxide fuel to the environment. In addition, two postulated very low probability (i.e., much lower than the probabilities for Phases 1 through 6) accident sce- narios that could occur during the interplanetary portions of the VVEJGA and VEEGA tra- jectories were identified as the short-term and long-term inadvertent reentry scenarios. The short-term scenario would involve the inadvertent reentry of the spacecraft into the Earth's atmosphere during a planned Earth swingby, and the long-term scenario would involve a spacecraft failure that leaves the spacecraft drifting in an Earth-crossing orbit and potentially reentering the Earth's atmosphere a decade to millennia later. Preliminary estimates for a Titan IV (SRM)/Centaur launch indicate that the radiological conse- quences and the risk would be similar to those for the Titan IV (SRMU)/Centaur. Depending on the accident scenario, the CCAS/KSC regional area, limited portions of the African continent under the vehicle flight path, or indeterminate locations within the global area could be impacted by plutonium dioxide fuel releases. The CCAS/KSC regional area could be impacted if a Phase 1 accident were to result in a release. Areas out- side the region (i.e., portions of the African continent; areas elsewhere around the world) could be impacted if an accident resulting in a release were to occur in Phase 5 or 6. Considering potential accidents that could result in a release across all launch phases, no excess cancer fatalities would be expected in the exposed population. No releases of plu- tonium from the RTGs to the environment are postulated if any of the representative acci- dent scenarios occurred in Phases 2, 3, or 4. During the interplanetary portions of the mission, postulated short- and long-term inadvertent reentry accident scenarios could result in releases of plutonium dioxide to the environment. However, NASA is designing the mission to avoid the potential for such acci- dents. The mission's design ensures that the expected probability of an inadvertent reen- try would be less than one in a million. If such an accident were to occur, plutonium

EXPLORING THE UNKNOWN 479 dioxide could be released in the upper atmosphere and/or scattered in indeterminate locations on the Earth's surface. Within the exposed population of 5 billion people, approximately 1 billion people (i.e., 20 percent or 1/5 of the population) would be expected to die of cancer due to other causes. The estimated fatalities that could result from an inadvertent reentry with release would represent an additional 0.0005 percent above the normally observed 1 billion cancer fatalities. The principal method used in this document for characterizing the radiological impacts of each alternative evaluated is health effects risk. Health effects are expressed as the number of excess latent cancer fatalities (above the normally observed cancer fatali- ties) caused by exposure to the plutonium dioxide fuel. As used in this FEIS, health effects mission risk is the probability of an accident with a plutonium dioxide fuel release (i.e., the probability of an initiating accident times the probability of that accident causing a release of plutonium dioxide, since not all accidents would result in a plutonium dioxide release) multiplied by the consequences of that accident (i.e., the health effects that could be caused by the exposure of individuals to the plutonium dioxide), summed over all pos- tulated accidents. Estimates of health effects mission risk, as discussed in this FEIS, repre- sent the expectation latent cancer fatalities. The expectation health effects mission risk over all mission phases (i.e., the total or overall health effects mission risk) does not include contributions to risk from the long-term reentry scenario. [ix] For the Proposed Action, the health effects mission risk considering all launch phas- es for the primary launch opportunity would be 8.4 x 107. The health effects mission risk from the short-term inadvertent reentry accident during the Earth swingby portion of the primary launch opportunity's VVEJGA trajectory would be 1.7 x $10^3$ and for the secondary and backup opportunities' VEEGA trajectories would be 1.8 x 103. The total health effects mission risk (considering all launch phases and the Earth-Gravity-Assist trajectories) from the primary launch opportunity would be 1.7 x 103 and from the backup launch oppor- tunity would be 1.8 x 103. The health effects mission risks from the Cassini mission would be small and less than the total health risks faced by the public from construction and/or operation of large industrial projects. The environmental impacts of a normal launch of the 1999 mission would be associat- ed with the normal operations of the Shuttle. These Shuttle operations would result in tem- porary impacts on air and water quality near the launch site. Because this alternative would require two Shuttle launches, impacts would occur two times separated by 21 to 51 days. During the second Shuttle launch for this mission alternative, certain accidents that may occur could result in a release of a portion of the plutonium dioxide from the RTGS to the environment. The local CCAS/KSC regional area could be impacted if a Phase 1 accident resulted in a release. Limited portions of the African land mass could be impact- ed by a Phase 2 accident, and Phases 3 and 4 accidents could impact indeterminate loca- tions within the global area. In addition, releases could occur from an accident occurring during a short-term inadvertent reentry. Potential failures and radiological consequences associated with the Earth swingby portions of the VEEGA trajectory would be expected to be identical to those analyzed for the VEEGA swingbys for the 1999 backup launch opportunity of the Proposed Action. Using estimation methods similar to that for the Proposed Action, the health effects mission risk over all the mission launch phases for the 1999 mission alternative is 2.1 x 106. The corresponding risk from a short-term inadvertent reentry during the Earth swingby portion of the VEEGA trajectories would be 1.8 x 103, and the total health effects mission risk would be 1.8 x 10.3. The environmental impacts of a normal launch of the 2001 mission alternative would be similar to those estimated for the Proposed Action. The spacecraft with a high performance rhenium propulsion engine would be launched on the Titan IV (SRMU)/Centaur. The launch accident scenarios that could result in a release of plu- tonium dioxide fuel and the associated consequences and risks would be identical to those evaluated for the Proposed Action. The overall health effects mission risk from the launch phases is 8.4 x 107. The primary launch opportunity of this 2001 mission alternative would not use the Earth for a gravity-assist (the trajectory is a VVVGA); sub- sequently, there would be no consequences and health effects mission risks associated with a short-term inadvertent reentry. Because there is no non-EGA backup launch opportunity for the 2001 mission alternative, the backup opportunity would use a VEEGA. The health effects mission risk from the backup short-term inadvertent reen- try is 1.8 x 103. The overall [x] health effects mission risk from the primary opportu- nity is 8.4 x 107 and from the backup is 1.8 x 10-3. For all launch opportunities, should the spacecraft become uncommandable any time after injection into its interplanetary trajectory and before the final planetary gravity-assist, the spacecraft could eventually reenter the Earth's atmosphere a decade to centuries later (i.e., long-term inadvertent reentry scenario). The health effects mission risk of such an event is assumed to be similar (i.e., same order of magnitude) to that estimated for the short-term inadvertent reentry for the primary launch opportunity associated with the Proposed Action. No environmental impacts would be associated with the No-Action alternative. MISSION-SPECIFIC CONSIDERATIONS The Proposed Action has the greatest potential to accomplish the mission and its sci- entific objectives. In addition, because the Proposed Action would ensure that adequate performance margins are available (e.g., spacecraft propellant available for maneuvers during the Saturn science tour), it would have the greatest likelihood to take advantage of both planned and unplanned opportunities for science return. The expected science return for the Proposed Action's December 1997 and March 1999 contingency launch opportunities would be less due to the later arrival time at Saturn. For similar reasons, the expected science return for the 1999 mission alternative using the two-Shuttle launch would be less than the return obtained from the Proposed Action. Although the 2001 mission alternative would achieve most of the planned science objectives, it would not return as much science as the Proposed Action. The larger pro- pellant tank and propellant load would reduce the overall mission performance, requir- ing the use of a specially developed rhenium spacecraft propulsion engine. Even with the use of this more efficient propulsion engine, the number of Titan flybys would be reduced from 35 to 21. Other trajectory adjustments would be necessary to conserve propellant. In addition to reducing the opportunity for obtaining the planned science return, the abili- ty of the spacecraft to take advantage of unplanned discoveries would be limited. Because

EXPLORING THE UNKNOWN 481 this alternative requires a longer flight time than the Proposed Action, and the launch would be delayed relative to the primary launch opportunity, the international partner- ships formed to develop the Cassini spacecraft, Huygens Probe, and other space-related projects could be disrupted. Because the No-Action alternative would cancel the mission, the science return would be lost, and the ability of the United States to enter into future international agreements for cooperative space activities could be impaired. [cover page] Document II-42 FINAL SUPPLEMENTAL ENVIRONMENTAL IMPACT STATEMENT FOR THE CASSINI MISSION Office of Space Science National Aeronautics and Space Administration Washington, DC 20546 June 1997 [iii] EXECUTIVE SUMMARY This Supplemental Environmental Impact Statement (SEIS) has been prepared in accordance with the National Environmental Policy Act of 1969 (NEPA), as amended (42 U.S.C. 4321 et. seq.); the Council on Environmental Quality Regulations for Implementing the Procedural Provisions of NEPA (40 CFR Parts 1500-1508); and the National Aeronautics and Space Administration's (NASA's) policy and procedures (14 CFR Subpart 1216.3) to support the decision-making process concerning the Proposed Action and alternatives for NASA's Cassini space exploration mission. NASA completed development of the Cassini mission Environmental Impact Statement (hereafter denoted 1995 Cassini EIS) with distribution of the Final EIS to the public and other interested parties in July 1995. The Record of Decision (ROD) was ren- dered in October 1995. The 1995 Cassini EIS contained NASA's evaluation of the poten- tial impacts of completing preparations for and implementing the Cassini mission, with particular emphasis on accidents that could potentially occur during launch and cruise phases of the mission, and which could impact human health and the environment. While the 1995 Cassini EIS analyses used the best information available at that time, the 1995 Cassini EIS noted that NASA and the U.S. Department of Energy (DOE) were continuing to analyze and evaluate additional accident scenarios specific to the Cassini spacecraft and its launch vehicle and trajectory. In both the 1995 Cassini EIS and the ROD, NASA made the commitment that, should significant differences arise between the results of the ongo- ing analyses and the 1995 Cassini EIS, NASA would evaluate the information and make a determination regarding the need for additional NEPA documentation, including sup- plementing the 1995 Cassini EIS. Updates of the safety analyses in support of the 1995 Cassini EIS were recently made available to NASA. NASA has evaluated those analyses accordingly, and has determined that the purposes of NEPA are furthered by preparation of this SEIS. PURPOSE AND NEED FOR THE ACTION The Cassini mission is an international cooperative effort of NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI), to explore the planet Saturn and its envi- ronment. Saturn is the second-largest and second-most massive planet in the solar system, and has the largest, most visible, dynamic ring structure of all the planets. The mission is an important part of NASA's program for exploration of the solar system, the goal of which is to understand the system's birth and evolution. The Cassini mission involves a four-year sci- entific exploration of Saturn, its atmosphere, moons, rings and magnetosphere. The Cassini spacecraft consists of the Cassini Orbiter and the detachable Huygens Probe. The Cassini mission represents an important step in the exploratory phase of plane- tary science, with the detailed data that would be obtained from the mission providing an important basis for continuing Earth-based studies of the planets. There are five major [iv] areas of investigation planned for the Cassini Mission. An overview of each area of investigation follows: • The previous Pioneer and Voyager swingby missions to Saturn obtained only short- duration, remote-sensing measurements of the Saturnian atmosphere. These mea- surements have been sufficient to generally determine the basic composition, energy balance, temperature profile, and wind speeds in the planet's upper atmosphere. Cassini would further investigate cloud properties and atmospheric composition, wind patterns, and temperatures, as well as Saturn's internal structure, rotation, ionos- phere, and origin and evolution. The missions would involve orbits near the equator and the poles of Saturn so that the entire planet could be studied. Titan is shrouded by dense clouds; therefore, little is known about its surface. Data collected by the instruments onboard the Cassini orbiter and the Huygens Probe would provide a better understanding of the abundance of elements and compounds in Titan's atmosphere, the distribution of trace gases and aerosols, winds and tem- perature, and surface state and composition. In particular, the spacecraft's radar would penetrate Titan's dense atmosphere and reveal the moon's surface character- istics. The Huygens Probe, carrying a robotic laboratory, would perform chemical analyses of Titan's atmosphere and clouds. As the Probe descends, the onboard instruments would measure the temperature, pressure, density, and energy balance through the atmosphere to the moon's surface. The surface properties would be mea- sured remotely, and a camera would photograph the Titan panorama and relay the images to Earth via the Cassini Orbiter.

EXPLORING THE UNKNOWN 483 • Saturn's other satellites (i.e., moons) are ice-covered bodies. Cassini would investigate their physical characteristics, the composition and distribution of materials on their surfaces, their internal structure, and how they interact with Saturn's magnetosphere. Of particular interest is the half-dark and half-light moon, Iapetus. The light side of the moon is believed to be composed of ice and the dark side possibly of some organ- ic material. The data obtained by Cassini would assist in determining the geological histories of the satellites and the evolution of their surface characteristics. The Voyager swingbys in 1980 and 1981 proved Saturn's ring system to be much more complex than previously realized, with intricate dynamic interactions in most parts of the system. The short-term Voyager studies showed a wide range of unexplained phe- nomena in the rings, including various wave patterns, small and large gaps, clumping of material and small, so-called “moonlets” embedded in the rings. Long-term, close- up observations of the rings by Cassini could help resolve whether the rings are mate- rial left over from Saturn's original formation, or whether they are remnants of one or more moons shattered by comet or meteor strikes. Applied to larger-scale disk- shaped systems, the detailed studies of Saturn's rings proposed for Cassini would pro- vide important contributions to theories of the origin and evolution of the dust and gas from which the planets first formed. [v] The tilt of Saturn's ring plane changes as the planet orbits the Sun and the chang- ing angle of sunlight illuminating the rings dramatically alters their visibility. Cassini's arrival at Saturn is timed for optimum viewing of the rings, during a period when they will be well illuminated by sunlight. Upon Cassini's arrival at Saturn in 2004 when launched in October 1997, the tilt of the ring plane and resulting illumination angle would allow Cassini's instruments an unsurpassed view of the ring disk. Cassini would allow detailed studies of ring structure and composition, dynamic processes, dust and micrometeoroid environments, and interactions among the ring systems, magnetosphere, and satellites. Saturn's magnetosphere is the region of space under the dominant influence of the planet's magnetic field. Cassini would carry instruments to study the configuration and dynamics of the magnetosphere; the nature, source, and fate of its trapped par- ticles; and its interactions with the solar wind and Saturn's satellites and rings. A par- ticular phenomenon of interest is the Saturn Kilometric Radiation—a poorly understood, very low frequency, electromagnetic radiation—which scientists believe is emitted by the auroral regions in Saturn's high latitudes. Implementation of the proposed action would also ensure that the spacecraft would complete its orbital tour before 2010, when Saturn's rings would present themselves near- ly edge-on to the Earth and Sun, severely limiting the ability for detailed observations. The Cassini spacecraft incorporates three (3) Radioisotope Thermoelectric Generators (RTGS) to provide onboard electric power for spacecraft operation and sci- entific instruments. The RTGs generate electric power by utilizing the heat from decay of

484 NASA AND PLANETARY EXPLORATION radioactive material. The material is an isotopic mixture of plutonium in the form of diox- ide, along with small amounts of long-lived actinides and other impurities. About 71 per- cent of the oxide mixture (by weight) is plutonium-238 (Pu-238). The three RTGS onboard the Cassini spacecraft contain a total of 32.7 kg (about 72 lb) of PuO2, amount- ing to 1.49x1016 Bq (402,000 Ci). In addition, 129 Radioisotope Heater Units (RHUs) will be employed to regulate the temperature inside the spacecraft and for several instru- ments. Each RHU contains about 2.7 gm (0.006 lb) of mostly plutonium-238 dioxide, amounting to a collective total of about 0.35 kg (0.77 lb), or about 1.48x1014 Bq (4,000 Ci) of radioactive material in the 129 RHUS. The 1995 Cassini EIS was made available to Federal, state and local agencies, the pub- lic and other interested parties on July 21, 1995. In addition to the No-Action Alternative, the 1995 Cassini EIS addressed three alternatives for completing preparations for and operating the Cassini mission to Saturn and its moons. On October 20, 1995, utilizing the impact analyses in the EIS, along with other important considerations such as [vi] pro- grammatic, economic, and international relations, the ROD selecting the Proposed Action was rendered. ALTERNATIVES EVALUATED The Proposed Action and preferred alternative consists of completing preparations for and operating the Cassini mission to Saturn and its moons, with a launch of the Cassini spacecraft onboard a Titan IV (SRMU)/Centaur. The launch would take place at Cape Canaveral Air Station (CCAS) during the primary launch opportunity of October 6 through November 15, 1997. A secondary launch opportunity occurs from late November 1997 through early January 1998, with a backup opportunity from mid-March to early April 1999, both using the Titan IV (SRMU)/Centaur. The primary launch opportunity would employ a Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) trajectory to Saturn; the secondary and backup opportunities would both employ a Venus-Earth-Earth-Gravity- Assist (VEEGA) trajectory. The Proposed Action would allow the Cassini spacecraft to gather the full science return desired to accomplish mission objectives. Along with the No-Action Alternative, the 1995 Cassini EIS evaluated two other mis- sion alternatives. The March 1999 Alternative would have used two Shuttle flights launched from Kennedy Space Center (KSC), with on-orbit integration of the spacecraft and upper stage, followed by injection of the spacecraft into a VEEGA trajectory to Saturn. The March 1999 Alternative is no longer considered reasonable at this time due to the long lead-time in developing and certifying the new upper stage that would be needed to implement this mission alternative. When combined with the significant addi- tional costs associated with this alternative, the 1999 dual Shuttle alternative is no longer considered reasonable. The other mission alternative evaluated in the 1995 Cassini EIS was the 2001 Alternative, which would use a Titan IV (SRMU)/Centaur to launch the spacecraft from CCAS in March 2001 using a Venus-Venus-Venus-Gravity-Assist (VVVGA) trajectory. A backup opportunity in May 2002 would use a VEEGA trajectory. The 2001 Alternative would require completing the development and testing of a new high-performance rhe- nium engine for the spacecraft, as well as adding about 20 percent more propellant to the

EXPLORING THE UNKNOWN 485 spacecraft. Science returns from this alternative would meet the minimum acceptable level for the mission. RADIOLOGICAL IMPACTS OF ACCIDENTS Evaluation of the recently available safety analyses has indicated that the only parts of the previous Cassini EIS potentially affected are the analyses of the radiological conse- quences of accidents involving a potential release of plutonium dioxide (source term) from the RTGs and/or the RHUs onboard the spacecraft. The environmental impacts of completing preparations for the mission are unaffected by the updated analyses, and [vii] remain as presented in the 1995 Cassini EIS. In addition, the analyses of the environ- mental impacts of both an incident-free launch and incident-free interplanetary gravity- assist trajectory are also unaffected and remain as presented in the 1995 Cassini EIS. The EIS's and recently available analyses overall assessments of the Cassini mission's risk are similar. The updated assessment of individual mission segment accidents has iden- tified higher risks for launch segment accidents and lower risks for the Earth gravity assist (EGA) swingby segment. Both the EIS and the updated analyses indicate that only a frac- tion of conceivable launch accidents are calculated to result in releases of PuO2. The ongoing safety analysis process is similar to the process used for the earlier Galileo and Ulysses missions and has resulted in incremental improvements in the mod- eling and analysis techniques. The potential source terms are determined by using simu- lations to evaluate the response of the RTGS, RTG components, and RHUs to the defined accident environments. The ongoing analyses utilize probabilistic risk assessment tech- niques with computer simulation and modeling of RTG responses to accident environ- ments, and are based upon safety test and analysis studies performed by and on behalf of DOE. The safety test and analysis studies have been performed over the past 12 years on General Purpose Heat Source (GPHS) RTGS and materials, and RHUS. These tests pro- vide a database of the performance response of the RTGS and RHUs to simulated accident conditions such as high-velocity impacts on hard surfaces, impacts from high-velocity frag- ments, and exposure to thermal and mechanical stresses such as would be encountered in a reentry from Earth orbit or exposure to burning solid rocket motor propellant. It must be emphasized that for a release of plutonium dioxide (PuO2) to occur, the initiating accident must be followed by other events to create an accident environment that threat- ens the integrity of the RTGS and RHUS. Since the issuance of the 1995 Cassini EIS, the refinements in the evaluation of accidents and estimation of their potential consequences have resulted in revised estimates. Comparison between the 1995 Cassini EIS results and the updated results are presented in this SEIS. The 1995 Cassini EIS reported point estimates of the “expectation” and “maximum” cases. The expectation case utilized source terms for each accident scenario that were probability-weight- ed, and was based upon a range of release conditions considered in the analysis. The maxi- mum case utilized source terms that corresponded to either the upper limit deemed credible for the scenario, based on consideration of supporting analyses and safety test data, or to a total probability greater than or equal to a probability cutoff of 1x107 (1 in 10 million). The updat- ed analyses used probabilistic risk assessment techniques similar to those used for the Galileo and Ulysses missions to generate updated estimates of consequences and risk.

486 NASA AND PLANETARY EXPLORATION The 1995 Cassini EIS utilized the concept of risk as one of the key measures in the acci- dent analyses. Risk, for the purpose of the 1995 Cassini EIS and for this supplement, is defined as the total probability of an event occurring (i.e., a release from an RTG or RHU), multiplied by the mean consequence of the event (i.e., health effects described as latent [viii] cancer fatal- ities over a 50-year period within the population potentially exposed by an accident). With respect to the Cassini accident analyses, the total probability of a release occurring is deter- mined by multiplying the probability of the initiating accident that could threaten the RTGS and RHUS, times the conditional probability that the accident will result in a release. Risk esti- mates for the Cassini mission (expressed as health effects) have been developed for each mis- sion phase/accident scenario and for the average exposed individual. The updated analyses report the best estimate of consequences and risks. While the overall probability of an accident that could threaten the RTGs or RHUs during the Cassini mission is $2.8x10^2$, or 1 in 36, the probability of an accident predicted to release PuO2 is $2.8x10^3$, or less than 1 in 357. Such an accident could result in 0.089 mean health effects. This results in an overall mission risk of 2.5x104, or 0.00025, health effects worldwide. This risk level is lower than the overall risk reported in the 1995 Cassini EIS (expected value of $1.7x10^3$, or 0.0017, health effects). The total mission risk is distributed over four major mission segments—i.e., pre-launch (Phase 0), early launch (Phases 1 and 2), late launch (Phases 3-8) and Earth Gravity Assist (EGA). The pre-launch segment runs from 48 hours (T-48 hrs) prior to launch to T-0 sec- onds (s). The early launch segment starts with ignition of the SRMUs at T-0 s and extends through T+143 s when the SRMUs are jettisoned. The time period from T+143 s to T+206 s is not considered because there are no accidents that could result in a release of PuO2 during this time period of the mission. The late launch segment starts at T+206 s and extends to the point where the spacecraft has escaped from Earth orbit. The EGA segment encompasses the period from Earth escape to completion of the Earth swingby. Pre-launch accidents were not covered in the 1995 Cassini EIS because, at that time, none were postulated that could result in a release of PuO2. However, information recent- ly made available from the updated mission safety analyses indicates the total probability of a pre-launch accident that results in a release of PuO2 is 5.2x105, or about 1 in 19,200, and could result in 0.11 mean health effects and could contaminate 1.5 km2 ($0.58 mi^2$) of land above $7.4x10^3$ $Bq/m^2$ ($0.2 \mu Ci/m^2$) (the Environmental Protection Agency's [EPA's] guideline level for considering the need for further action). The total probability of an early launch accident that results in a release of plutonium is 6.7x104, or about 1 in 1,490, and could result in 0.082 mean health effects and could contaminate 1.6 $km^2$ ($0.62 mi^2$) of land above the EPA guideline level. In comparison to the 1995 Cassini EIS, this segment's mean mission risk is 0.000055 health effects, which exceeds the 1995 Cassini EIS estimate of 0.00000046. The total probability of a late launch accident that results in a release of plutonium is 2.1x103, or 1 in 476, and could result in 0.044 mean health effects and could contaminate 0.057 $km^2$ ($0.02 mi^2$) of land above the EPA guideline level. In comparison to the 1995 Cassini EIS, this segment's mean mission risk is 0.000092 health effects, which exceeds the 1995 Cassini EIS estimate of 0.00000037. [ix] The total probability of an EGA accident that results in a release of plutonium is 8.0x107, or less than 1 in 1 million, and could result in 120 mean health effects and could contaminate 15 $km^2$ ($5.8 mi^2$) of land above the EPA guideline level. In comparison to the

EXPLORING THE UNKNOWN 487 1995 Cassini EIS, this segment's mean mission risk is 0.000098 health effects, which is less than the 1995 Cassini EIS estimate of 0.0017. In addition to these new best estimate analyses, DOE has conducted a study of the uncertainty in the underlying test data and models used to estimate accident risks and consequences. This information is presented in Chapter 4 of this SEIS. Document II-43 Document title: "Statement from Daniel S. Goldin, NASA Administrator," NASA Press Release 96-159, August 6, 1996. Source: Office of Public Affairs, NASA Headquarters, Washington, D.C. Document II-44 Document title: "Meteorite Yields Evidence of Primitive Life on Early Mars," NASA Press Release 96-160, August 7, 1996. Source: Office of Public Affairs, NASA Headquarters, Washington, D.C. Document II-45 Document title: "President Clinton Remarks," August 7, 1996. Source: Office of the Press Secretary, The White House, Washington, D.C. Document II-46 Document title: Mars Expeditions Strategy Group, "The Search for Evidence of Life on Mars," September 26, 1996. Source: Office of Space Science, NASA, Washington, D.C. Mars captivated the attention of NASA and the public worldwide in 1996. That summer, a NASA-fund- ed research team announced in the journal Science that it had identified evidence of organic molecules in a Martian meteorite found in Antarctica, which suggested that primitive life may have existed on early Mars. As these documents illustrate, the discovery stimulated enthusiasm at NASA and across the nation for Mars exploration. Prior to the meteorite study, NASA had initiated a program of Mars exploration in which the agency planned to send two spacecraft, an orbiter and a lander, to Mars about every two years over a decade's time. Determined to make the search for life its overarching goal for Mars exploration after the announcement, NASA formed a multidisciplinary group of scientists to develop strategies for search- ing for signs of life on future missions. The last document is an excerpt from the group's report.

488 NASA AND PLANETARY EXPLORATION [no pagination] Laurie Boeder Headquarters, Washington, DC (Phone: 202/358-1898) RELEASE: 96-159 Document II-43 August 6, 1996 STATEMENT FROM DANIEL S. GOLDIN, NASA ADMINISTRATOR “NASA has made a startling discovery that points to the possibility that a primitive form of microscopic life may have existed on Mars more than three billion years ago. The research is based on a sophisticated examination of an ancient Martian meteorite that landed on Earth some 13,000 years ago. The evidence is exciting, even compelling, but not conclusive. It is a discovery that demands further scientific investigation. NASA is ready to assist the process of rigorous sci- entific investigation and lively scientific debate that will follow this discovery. I want everyone to understand that we are not talking about 'little green men.' These are extremely small, single-cell structures that somewhat resemble bacteria on Earth. There is no evidence or suggestion that any higher life form ever existed on Mars. The NASA scientists and researchers who made this discovery will be available at a news conference tomorrow to discuss their findings. They will outline the step-by-step 'detective story' that explains how the meteorite arrived here from Mars, and how they set about looking for evidence of long-ago life in this ancient rock. They will also release some fascinating images documenting their research." [no pagination] Donald L. Savage Headquarters, Washington, DC (Phone: 202/358-1727) James Hartsfield Johnson Space Center, Houston, TX (Phone: 713/483-5111) David Salisbury Stanford University, Palo Alto, CA (Phone: 415/723-2558) Document II-44 August 7, 1996

EXPLORING THE UNKNOWN 489 RELEASE: 96-160 METEORITE YIELDS EVIDENCE OF PRIMITIVE LIFE ON EARLY MARS A NASA research team of scientists at the Johnson Space Center (JSC), Houston, TX, and at Stanford University, Palo Alto, CA, has found evidence that strongly suggests prim- itive life may have existed on Mars more than 3.6 billion years ago. The NASA-funded team found the first organic molecules thought to be of Martian origin; several mineral features characteristic of biological activity; and possible micro- scopic fossils of primitive, bacteria-like organisms inside of an ancient Martian rock that fell to Earth as a meteorite. This array of indirect evidence of past life will be reported in the August 16 issue of the journal Science, presenting the investigation to the scientific community at large for further study. The two-year investigation was co-led by JSC planetary scientists Dr. David McKay, Dr. Everett Gibson and Kathie Thomas-Keprta of Lockheed-Martin, with the major collabora- tion of a Stanford team headed by Professor of Chemistry Dr. Richard Zare, as well as six other NASA and university research partners. "There is not any one finding that leads us to believe that this is evidence of past life on Mars. Rather, it is a combination of many things that we have found," McKay said. "They include Stanford's detection of an apparently unique pattern of organic molecules, carbon compounds that are the basis of life. We also found several unusual mineral phas- es that are known products of primitive microscopic organisms on Earth. Structures that could be microsopic [sic] fossils seem to support all of this. The relationship of all of these things in terms of location-within a few hundred thousandths of an inch of one anoth- er■is the most compelling evidence." "It is very difficult to prove life existed 3.6 billion years ago on Earth, let alone on Mars," Zare said. "The existing standard of proof, which we think we have met, includes having an accurately dated sample that contains native microfossils, mineralogical fea- tures characteristic of life, and evidence of complex organic chemistry." "For two years, we have applied state-of-the-art technology to perform these analyses, and we believe we have found quite reasonable evidence of past life on Mars," Gibson added. "We don't claim that we have conclusively proven it. We are putting this evidence out to the scientific community for other investigators to verify, enhance, attack—disprove if they can■as part of the scientific process. Then, within a year or two, we hope to resolve the question one way or the other." "What we have found to be the most reasonable interpretation is of such radical nature that it will only be accepted or rejected after other groups either confirm our find- ings or overturn them," McKay added. The igneous rock in the 4.2-pound, potato-sized meteorite has been age-dated to about 4.5 billion years, the period when the planet Mars formed. The rock is believed to have originated underneath the Martian surface and to have been extensively fractured by impacts as meteorites bombarded the planets in the early inner solar system. Between 3.6 billion and 4 billion years ago, a time when it is generally thought that the planet was warmer and wetter, water is believed to have penetrated fractures in the subsurface rock, possibly forming an underground water system.

 Since the water was saturated with carbon dioxide from the Martian atmosphere, car- bonate minerals were deposited in the fractures. The team's findings indicate living organisms also may have assisted in the formation of the carbonate, and some remains of the microscopic organisms may have become fossilized, in a fashion similar to the forma- tion of fossils in limestone on Earth. Then, 16 million years ago, a huge comet or asteroid struck Mars, ejecting a piece of the rock from its subsurface location with enough force to escape the planet. For millions of years, the chunk of rock floated through space. It encountered Earth's atmosphere 13,000 years ago and fell in Antarctica as a meteorite. It is in the tiny globs of carbonate that the researchers found a number of features that can be interpreted as suggesting past life. Stanford researchers found easily detectable amounts of organic molecules called polycyclic aromatic hydrocarbons (PAHs) concentrated in the vicinity of the carbonate. Researchers at JSC found mineral com- pounds commonly associated with microscopic organisms and the possible microscopic fossil structures. The largest of the possible fossils are less than 1/100 the diameter of a human hair, and most are about 1/1000 the diameter of a human hair—small enough that it would take about a thousand laid end-to-end to span the dot at the end of this sentence. Some are egg-shaped while others are tubular. In appearance and size, the structures are strik- ingly-similar to microscopic fossils of the tiniest bacteria found on Earth. The meteorite, called ALH84001, was found in 1984 in Allan Hills ice field, Antarctica, by an annual expedition of the National Science Foundation's Antarctic Meteorite Program. It was preserved for study in JSC's Meteorite Processing Laboratory and its possible Martian origin was not recognized until 1993. It is one of only 12 mete- orites identified so far that match the unique Martian chemistry measured by the Viking spacecraft that landed on Mars in 1976. ALH84001 is by far the oldest of the 12 Martian meteorites, more than three times as old as any other. Many of the team's findings were made possible only because of very recent techno- logical advances in high-resolution scanning electron microscopy and laser mass spec- trometry. Only a few years ago, many of the features that they report were undetectable. Although past studies of this meteorite and others of Martian origin failed to detect evi- dence of past life, they were generally performed using lower levels of magnification, with- out the benefit of the technology used in this research. The recent discovery of extremely small bacteria on Earth, called nanobacteria, prompted the team to perform this work at a much finer scale than past efforts. The nine authors of the Science report include McKay, Gibson and Thomas-Keprta of JSC; Christopher Romanek, formerly a National Research Council post-doctoral fellow at JSC who is now a staff scientist at the Savannah River Ecology Laboratory at the University of Georgia; Hojatollah Vali, a National Research Council post-doctoral fellow at JSC and a staff scientist at McGill University, Montreal, Quebec, Canada; and Zare, graduate stu- dents Simon J. Clemett and Claude R. Maechling and post-doctoral student Xavier Chillier of the Stanford University Department of Chemistry. The team of researchers includes a wide variety of expertise, including microbiology, mineralogy, analytical techniques, geochemistry and organic chemistry, and the analysis crossed all of these disciplines. Further details on the findings presented in the Science arti- cle include:

EXPLORING THE UNKNOWN 491 * Researchers at Stanford University used a dual laser mass spectrometer-the most sensitive instrument of its type in the world—to look for the presence of the common fam- ily of organic molecules called PAHs. When microorganisms die, the complex organic molecules that they contain frequently degrade into PAHs. PAHs are often associated with ancient sedimentary rocks, coals and petroleum on Earth and can be common air pollu- tants. Not only did the scientists find PAHs in easily detectable amounts in ALH84001, but they found that these molecules were concentrated in the vicinity of the carbonate glob- ules. This finding appears consistent with the proposition that they are a result of the fos- silization process. In addition, the unique composition of the meteorite's PAHs is consistent with what the scientists expect from the fossilization of very primitive microor- ganisms. On Earth, PAHs virtually always occur in thousands of forms, but, in the mete- orite, they are dominated by only about a half-dozen different compounds. The simplicity of this mixture, combined with the lack of lightweight PAHs like napthalene, also differs substantially from that of PAHs previously measured in non-Martian meteorites. * The team found unusual compounds—iron sulfides and magnetite—that can be pro- duced by anaerobic bacteria and other microscopic organisms on Earth. The compounds were found in locations directly associated with the fossil-like structures and carbonate globules in the meteorite. Extreme conditions-conditions very unlikely to have been encountered by the meteorite-would have been required to produce these compounds in close proximity to one another if life were not involved. The carbonate also con- tained tiny grains of magnetite that are almost identical to magnetic fossil remnants often left by certain bacteria found on Earth. Other minerals commonly associated with biolog- ical activity on Earth were found in the carbonate as well. * The formation of the carbonate or fossils by living organisms while the meteorite was in the Antarctic was deemed unlikely for several reasons. The carbonate was age dated using a parent-daughter isotope method and found to be 3.6 billion years old, and the organic molecules were first detected well within the ancient carbonate. In addition, the team analyzed representative samples of other meteorites from Antarctica and found no evidence of fossil-like structures, organic molecules or possible biologically produced compounds and minerals similar to those in the ALH84001 meteorite. The composition and location of PAHs organic molecules found in the meteorite also appeared to confirm that the possible evidence of life was extraterrestrial. No PAHs were found in the mete- orite's exterior crust, but the concentration of PAHs increased in the meteorite's interior to levels higher than ever found in Antarctica. Higher concentrations of PAHs would have likely been found on the exterior of the meteorite, decreasing toward the interior, if the organic molecules are the result of contamination of the meteorite on Earth. Additional information may be obtained at 1 p.m. EDT via the Internet at http://www.jsc.nasa.gov/pao/flash/

492 NASA AND PLANETARY EXPLORATION Document II-45 [no pagination] Subject: President Clinton remarks Date: Thursday, August 08, 1996 3:19PM THE WHITE HOUSE Office of the Press Secretary For Immediate Release August 7, 1996 REMARKS BY THE PRESIDENT UPON DEPARTURE The South Lawn 1:15 P.M. EDT THE PRESIDENT: Good afternoon. I'm glad to be joined by my science and tech- nology adviser, Dr. Jack Gibbons, to make a few comments about today's announcement by NASA. This is the product of years of exploration and months of intensive study by some of the world's most distinguished scientists. Like all discoveries, this one will and should continue to be reviewed, examined and scrutinized. It must be confirmed by other scientists. But clearly, the fact that something of this magnitude is being explored is another vindication of America's space program and our continuing support for it, even in these tough financial times. I am determined that the American space program will put its full intellectual power and technological prowess behind the search for further evidence of life on Mars. First, I have asked Administrator Goldin to ensure that this finding is subject to a methodical process of further peer review and validation. Second, I have asked the Vice President to convene at the White House before the end of the year a bipartisan space summit on the future of America's space program. A significant purpose of this summit will be to discuss how America should pursue answers to the scientific questions raised by this finding. Third, we are committed to the aggressive plan we have put in place for robotic exploration of Mars. America's next unmanned mission to Mars is scheduled to lift off from the Kennedy Space Center in November. It will be followed by a second mis- sion in December. I should tell you that the first mission is scheduled to land on Mars on July the 4th, 1997-Independence Day. It is well worth contemplating how we reached this moment of discovery. More than 4 billion years ago this piece of rock was formed as a part of the original crust of Mars. After billions of years it broke from the surface and began a 16 million year journey through space that would end here on Earth. It arrived in a meteor shower 13,000 years

EXPLORING THE UNKNOWN 493 ago. And in 1984 an American scientist on an annual U.S. government mission to search for meteors on Antarctica picked it up and took it to be studied. Appropriately, it was the first rock to be picked up that year-rock number 84001. Today, rock 84001 speaks to us across all those billions of years and millions of miles. It speaks of the possibility of life. If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered. Its implications are as far-reaching and awe-inspiring as can be imagined. Even as it promises answers to some of our oldest questions, it poses still others even more fundamental. We will continue to listen closely to what it has to say as we continue the search for answers and for knowledge that is as old as humanity itself but essential to our people's future. Thank you. Document II-46 [no pagination] The Search for Evidence of Life on Mars (Excerpt from report of Mars Expeditions Strategy Group Dan McCleese, JPL, Chairman) 26 September 1996 FOCUS Did life ever exist on Mars? A multi-disciplinary group of scientists brought together by the National Aeronautics and Space Administration [NASA] is currently developing a strategy to seek the answer to that question. When complete, this strategy will form the basis for NASA's future program of Mars exploration. This report is a statement of work- in-progress by the group to identify a systematic approach, using robotic space missions and laboratory analyses of samples returned to Earth, to understand the possible origin and evolution of life on Mars. NASA is today conducting a series of robotic missions to Mars with the goal of under- standing its climate, resources and potential for harboring past or present life. The mea- surements to be made have in common the study of water and its history on the planet. The first mission to return to the surface of Mars since the Viking spacecraft in 1976 will be launched in December of 1996. Also this year, an orbiter will begin regional and glob- al mapping of the surface, searching for sites potentially hospitable to life some time in the planet's past. HYPOTHESES The fundamental requirements for life as we know it are liquid water, an inventory of organic compounds, and an energy source for synthesizing complex organic molecules. Beyond these basics, we have yet to achieve consensus regarding either the environmental requirements or the processes of chemical evolution that lead to the origin of life. Comparisons of genetic sequences in living organisms suggest that the last common ances- tor of life on Earth may have been a sulfur-utilizing bacterium that lived at high tempera- tures. This implies that hydrothermal environments were important in the early evolution of the biosphere. Given that hydrothermal systems have also been shown to be energeti- cally favorable places for organic synthesis, some scientists believe that it was in such loca- tion that life actually originated. However, others argue quite convincingly for a low temperature origin of life. Unfortunately for attempts to resolve this controversy, plate tectonics and extensive recycling of the crust have obliterated any record of pre-biotic chemical evolution on Earth. The story is, however, quite different for Mars. The absence of plate tectonics sug- gests that the Martian crustal record is much better preserved than that on Earth. The cra- tering record on Mars implies that vast areas of the Martian southern highlands are older than 3.8 billion years. Analysis of meteorites from Mars indicates that some highland ter- ranes date back to the very earliest period of planetary evolution (~4.5 billion years), over- lapping the period on Earth when pre-biotic chemical evolution first gave rise to life. Thus, even if life never developed on Mars, any inventory of biogenic elements and organ- ic compounds that may be preserved in the rocks of the ancient cratered highlands will yield crucial information about the pre-biotic chemistry that led to living systems on Earth. ENVIRONMENTS The members of the Mars strategy group recommend that the search for life on Mars should be directed at locating and investigating, in detail, those environments on the planet which were potentially most favorable to the emergence (and persistence) of life. Three in particular can be cited for concentrated study: (a) Ancient ground water environments: early in the planet's history liquid water, regarded as prerequisite for life, appears to have been widespread beneath the surface and may have provided a clement environment for the origin of life. Intense energy was dissipated by impacts associated with the final stages of plane- tary accretion and, along with volcanism, could have created warm ground water circulation systems favorable for the origin of life. In this scenario, evidence for ancient habitats may be found in the heavily cratered terranes of the Martian highlands. (b) Ancient surface water environments: also during early Martian history, liquid water was apparently released from subsurface aquifers, flowed across the surface, and pooled in low-lying regions. Solar irradiance would have provided biologi- cally useful energy. During this period habitats may have been formed, with evi- dence of life preserved in water-lain sediments in the valley systems and basins found in the highlands. (c) Modern ground water environments: life may have formed at any time, including recently, in habitats where subsurface water or ice is geothermally heated to cre- ate warm ground water circulation systems. In addition, life may have survived

EXPLORING THE UNKNOWN 495 from an early epoch in places beneath the surface where liquid water is present. Given our present uncertainty about the environmental conditions necessary for the origin of life, and our limited knowledge of the geologic history of Mars, we urge strong- ly that the investigation strategy emphasize sampling at diverse sites. It is specifically rec- ommended that the implementation of the program of exploration of Mars be aimed at the study of a range of ancient and modern aqueous environments. These environments may be accessed by exploring the ejecta of young impact craters, by investigating materi- al accumulated in outflow channels, and by coring. NEEDED INVESTIGATIONS In-situ studies conducted on the surface of Mars are essential to our learning more about Martian environments and for selecting the best samples for collection. However, for the next 10 years or more, the essential analyses of selected samples must be done in laboratories on Earth. It is evident from studies of meteorites that it is difficult to predict the full suite of analytic techniques which will be needed to complete the analysis of returned samples. Further, based upon the results of the Viking landers and analyses of Martian meteorites, markers of life are thought to be at low concentrations and fossils, if present, are likely to be very small. Therefore, “high precision” (i.e., sophisticated, state- of-the-art) analytical techniques must be used, such as those found in only the most advanced laboratories here on Earth. We also believe that to achieve widely accepted confirmation of Martian life, all three of the following must be clearly identified and shown to be spatially and temporally cor- related within rock samples: 1) organic chemical signatures that are indicative of life, 2) morphological fossils (or living organisms), 3) supporting geochemical and/or miner- alogical evidence (e.g., clearly biogenic isotopic fractionation patterns, or the presence of unequivocal biominerals). These characteristics can not be properly evaluated without the return of a variety of Martian samples to Earth for interdisciplinary study in appropriate laboratories. Precursor orbital information must be obtained, as well, to select the best sites for surface studies. We can already say with reasonable certainty, however, that the ancient highlands represent a region of great potential, and that at least the initial focused stud- ies should be performed there. Maps of surface mineralogy will be needed to enhance investigations within the highlands and enable searches elsewhere. This work begins with the launch of the Mars Global Surveyor (MGS) later this year. Additional measure- ments from orbit at higher spatial resolution are essential to identify productive sites (e.g., regions containing carbonates) at scales accessible by surface rovers. In addition, instruments capable of identifying near-surface water, water bound in rocks, and sub- surface ice, would greatly accelerate and make more efficient our search for environ- ments suitable for life. We have found it useful to consider the factors that lead to the fossilization and long- term preservation of microorganisms and key compositional indicators in rocks. Based on studies of the microbial fossil record on Earth, the long-term preservation of organic signa- tures is most favored within sedimentary environments where aqueous minerals precipitate rapidly from solution, entrapping organic materials within an impermeable mineral matrix.

 The best host minerals are those that have long crustal residence times by virtue of being chemically stable. In ancient rock sequences on Earth, organic materials tend to be found in association with a fairly restricted number of sedimentary precipitates, which include sil- ica, phosphate, and carbonate. Preservation of polycyclic aromatic hydrocarbons within the carbonates of the Martian meteorite ALH 84001 indicates that such mineralization process- es were an effective means for capturing organic materials in the early Martian crustal envi- ronment and, importantly, for preserving them for billions of years. From these factors we judge that an implementation strategy for the initial phases of Mars exploration can already be affirmed: (1) For ancient ground water environments, a sample return mission can occur rela- tively soon, since the necessary precursor information for site selection is already available from existing orbital photogeologic data, including Mariner 9 and Viking imagery, or will be provided by Mars Surveyor orbiters in ‘96, ‘98 and ‘01. (2) For ancient surface water environments, orbital and surface exploration/charac- terization should precede sample return because identification of extensive areas of carbonates and evaporites is highly desirable. This implies the use of advanced orbital and in situ instruments for mineral characterization. Technologies which enable long-range surface exploration are also needed. (3) For modern ground water environments, additional means for the identification of thermally active regions will be needed. Techniques for location of subsurface water (i.e., liquid and ice) are also needed. Sample return missions will retrieve the most productive samples if they are support- ed by extensive searches, analyses and collections performed by sophisticated rovers. These should be capable of ranges of 10s of kilometers in order to explore geologically diverse sites. The specific samples to be returned to Earth would be selected using crite- ria that increase the probability of finding direct evidence of life as well as the geological context, age and climatic environment in which the materials were formed. In order to retrieve scientifically meaningful samples, significant constraints must be placed on the way samples are handled during collection and return to Earth. We antici- pate retrieving dry rocks and minerals for which mechanical preservation is a major fac- tor; self-abrasion or shake-induced disintegration of the samples must be minimized. Almost certainly, the rocks will have been exposed already at the Mars surface so that pack- ing can be accomplished using local Mars soils; individual containerization of different rocks might not be a strict requirement. For subsurface environments, where ices or brines are possible, sample materials must be handled in such a way that melting or evap- oration of volatiles within the samples can be controlled. For volatile-rich samples, tem- perature control, individual containerization, and hermetic sealing to prevent mass loss or mass exchange are likely to be requirements. If extant life is found, even more stringent environmental controls may be required. For samples from all environments, preservation protocols must address the sensitivity of biogeochemical materials (organic compounds plus minerals containing the chemical elements H, C, N, O, S, and P) to material conta-

EXPLORING THE UNKNOWN 497 mination and to thermal degradation. Unmodified samples of the Martian atmosphere must also be brought back to Earth where they can be examined in our laboratories. The possibility of the origin and evolu- tion of life on Mars must be fundamentally linked to the evolution of the atmosphere, through its contribution of biogenic elements and compounds (including water), through chemical reactions taking place at the atmosphere-surface interface and through regulation of the planetary climate. Although precise requirements for sizes or masses of samples require further evalua- tion, our preliminary recommendation is that individual rock samples should be on the order of at least 10-20 grams. Experience with planetary samples, including Martian mete- orites, has amply demonstrated that a representative 10-20-gram rock sample can be divid- ed effectively and distributed to state-of-the-art laboratories to accomplish all of the important measurements. Even though larger samples are desirable for certain types of studies, the Apollo lunar program taught us that a limited sample payload mass is more profitably expended on numerous small samples than on a few large ones. To summarize, our science strategy is predicated on the execution of several (at least three) mission sequences comprising precursor orbital and roving elements together with selected retrieval of samples for detailed analysis in Earth laboratories. To achieve effi- ciencies of time and cost, sample selection and caching may occur at more sites than sam- ple return. An endeavor of this nature involves a number of uncertainties and should be expected to encounter occasional setbacks. The overall structure and implementation of the program must be sufficiently flexible to accommodate these perturbations and to adjust to discoveries as it progresses. SAMPLE QUARANTINE By long-standing international agreement, spacefaring nations take measures to pro- tect planetary environments against biological cross-contamination during space explo- ration missions. We assume that some level of sample quarantine will be included in mission requirements. We recommend that any sample quarantine and sterilization pro- tocols be closely coordinated with plans for analysis of returned samples and we urge that care be taken throughout the planning process to assure that tradeoffs among quarantine, sterilization, and science goals are clearly understood before implementation plans are adopted. Even though sample quarantine probably will be conducted in a restricted-access facility, and some preliminary characterization of the samples will occur behind the quar- antine barriers, we believe that the maximum value of the samples can be extracted only if the samples are made available to scientists in their individual, specialized laboratories. Therefore, we recommend that, if sample quarantine and sterilization become opera- tional requirements, some provision be made so that sterilized samples can be released to outside research laboratories, with suitable controls, and at the earliest possible opportu- nity in the execution of the program. TECHNOLOGY REQUIREMENTS Although this group of scientists has only recently begun to develop a road map for enabling technologies, we can already see several technology needs emerging: I) Long-range rovers capable of surviving from months to years on the Martian surface. Rovers must be capable of carrying a sophisticated battery of tools and instruments over distances of 10s of km. II) Low-mass propulsion, power and communications systems for landed elements (e.g., Mars ascent vehicles and rovers). III) High spatial resolution (orbital) remote sensing instruments. Spectrometers and radiometers are needed for mineralogy and detection of thermally active regions. IV) In situ instruments, supported by sample preparation tools, able to identify aque- ous minerals in rocks and relative ages of samples. A report by a NASA ad hoc working group on instruments for exopaleontology includes descriptions of promising techniques (Point Clear Exobiology Instrumentation Workshop, 13-17 May 1996; T. J. Wdowiak, D. G. Agresti, J. Chang, Eds.). V) Tools are needed for shallow excavation, coring to depth, rock and soil manipu- lation, and sample preparation. Tools must be lightweight and low power. VI) Development of advanced terrestrial laboratory instrumentation. These requirements for technology will be refined and additional technologies iden- tified in the near future as the exploratory strategy unfolds. It is clear today, however, that development should proceed apace with long-lead technologies (e.g. instruments, rovers, propulsion systems). OPPORTUNITIES FOR INTERNATIONAL COLLABORATION We view the exploration of Mars to be inherently an international undertaking. The strategy outlined above is well suited to, and likely to be dependent upon, foreign involve- ment. Participation by non-U.S. scientists and agencies could range from participation in individual instruments to entire missions being sponsored abroad. HUMAN EXPLORATION The science strategy described above requires a series of robotic sample return mis- sions. This series may continue until either: (a) it has been conclusively shown that life existed on Mars at some time in the past; or (b) the evidence for Mars life is ambiguous, but little progress is being made, or expected, through additional robotic sample returns. (We note that it is impossi- ble to prove that life never arose on Mars.) In the former case, the questions of life's beginning, evolution and possible survival to the present become prominent scientifically. In the latter case, we will inevitably have learned much more about the environments that existed throughout Mars' history, but we will be hin- dered by lack of technology, lack of new ideas, or lack of resources. At present, we are encour- aged in (a) above by the discoveries in Antarctic Meteorite ALH 84001. In either case, a re-examination of the strategy will be necessary after analysis of the initial returned samples. Exploration involving humans may be required at this decision point. If past life were to be demonstrated, the questions then asked would be more complex, requiring sub- stantially larger amounts of data, a reconnaissance mode of exploration would no longer be sufficient, and the observational and analytical capabilities that could be provided by humans could be the more effective approach. If the data were still ambiguous, but promising, the need for human in situ capabilities could prove compelling. For example, if the search turns to locating and drilling for extant subsurface warm aqueous systems, the observational and manipulative skills of humans could be important. Thus, the per- ceived difficulties of making further progress could form the basis for a decision to con- duct human scientific exploration of Mars. The questions raised by the discovery of evidence for past or present life on Mars could become so important that they provide much of the rationale for human exploration. Whether human missions become practical and desirable either from the scientific perspective, or from other rationales, the robotic orbital, surface and sample return program will provide important information to support human missions, through (a) characterization of the surface environment in which humans must establish their pres- ence, such as the toxicity of dust, the availability of water, the radiation environment, and resolution of the forward/back-contamination issues; and (b) development and/or demonstration of technologies that would be used in human missions, such as Mars resource extraction systems, surface mobility, deep coring and analytical instrumenta- tion, among others. MARS METEORITE RESEARCH In addition to pursuing an exploration program focused on missions to the plan- et, we strongly endorse NASA's efforts aimed at increasing the number of Martian samples available for laboratory study through expanded support of the NSF/NASA/Smithsonian-sponsored Antarctic Search for Meteorites (ANSMET) pro- gram. Five Martian meteorites have been discovered through the US Antarctic pro- gram since 1977, and an additional sample has been documented (but not yet extensively studied) in the similar effort by Japanese Antarctic teams. For the US pro- gram alone, this corresponds to approximately one Martian meteorite per 1000 Antarctic meteorites collected, or one Martian rock per four seasons of meteorite col- lection. Mars Expeditions encourages investigation of ways in which the productivity of ANSMET-measured in terms of the area searched each season-can be increased to allow the rate of discovery of Martian meteorites to be accelerated. Re-examination of the methodologies used to locate, document and collect samples might allow such an increase in productivity without calling for an increase in the number of partici- pants involved in the field collection effort. In addition, NASA should expand the resources applied to the laboratory processing, cataloging, and organically clean han- dling of Martian meteorites so that research relevant to the search for Martian life can be supported at a faster pace. Methodologies used in the handling and study of meteorites from Mars are similar to those that will be applied to samples retrieved from Mars by spacecraft. Continued sup- port of ANSMET and Martian meteorite research will assist directly in preparation for eventual Mars sample analysis. It is our view moreover, that strong ties should be forged with other nations participating in meteorite searches (such as Japan) to further expand the effort. While we do not suggest that study of more meteorite samples will unequivo- cally answer the question of whether life ever existed on Mars, we have no doubt that

500 NASA AND PLANETARY EXPLORATION analysis of a larger set of Martian meteoritic materials will enhance our understanding of the geological and possible biological history of the planet. Mars Expeditions Strategy Group 26 September 1996

Chapter Three: Exploring the Universe: Space-Based Astronomy and Astrophysics Nancy Grace Roman 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 peo- ple 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 tele- scopes.[3] Although it had been 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 mil- lennia 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 early twen- tieth century could astronomers measure the motion of stars toward and away from 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. As helium is slightly lighter than four hydrogen atoms, this reaction changes a bit of matter into ener- gy. 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 1. In this essay, astronomical observations are defined as those focused on objects and phenomena exist- ing beyond the solar system. A short section on general relativity also is 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 increase 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 por- tion 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 cen- timeters. 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. 4. Hans Bethe, "Energy Production in Stars,” Physical Review 55 (1939): 434-56. 501

 lack of change. Observations in other wavelengths were to show how misleading the obser- vations in the visible region had been. In the 1930s, astronomer Karl Jansky first detected radio emissions from the cen- ter of the Milky Way.5 The first attempt to study celestial objects in wavelengths other Wavelength (nanometers) 8 106 10 10 10 10 0.01 1 100 10 104 1 nm 1 micron 1 mm 1 meter UV Gamma rays X-rays Infrared Radio Waves Blue Red 6 400 500 600 700 Visible Region Electromagnetic Spectrum than the visible was made as the result of the development of radar in the 1940s. Grote Reber, an amateur astronomer, observed strong emission from the constellation Sagittarius and weaker maxima in the constellations Cygnus, Cassiopeia, Canis Major, and Puppis. 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. Other radio emissions 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. In spite of the weakness of the transition, scientists soon observed a great abundance of hydrogen between the stars. 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 multi- ple 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 5. Karl Jansky, “Electrical Disturbances Apparently of Extraterrestrial Origin,” Proceedings of the Institute of Radio Engineers 21 (1933): 1387-98. Grote Reber, "Cosmic Static," Astrophysical Journal 100 (1944): 279-87. 6. 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.

EXPLORING THE UNKNOWN 503 dense star fields any finer than those that can be seen easily with a good amateur tele- scope. Second, and almost as important, the constituents of the atmosphere block 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 atmos- phere 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 Earth is never completely dark. For these reasons, some astronomers became interested in the possibility of observa- tions from above the atmosphere.¹ 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." [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 con- junction with a human-occupied space station, but not attached to the station.¹ 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 infor- mation on these experiments.) The first celestial photograph taken from a scientific payload flown on a V-2 was a spectrum of the Sun, 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 spectro- graph for stellar observations. The rocket on which the experiment rode failed, as many oth- ers did in these early years." 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 astro- nomical 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 10. Others, however, were skeptical of the usefulness of observing the heavens from space. See the sec- tion 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). 12. Fred L. Whipple, Lecture at Second Symposium on Space Travel at the Hayden Planetarium, American Museum of Natural History, New York, NY, 1952. 781-82. 13. W. A. Baum et al., “Solar Ultraviolet Spectrum to 88 Kilometers,” Physical Review 70 (November 1946): 14. After his experiment's failure, Greenstein promised to have nothing more to do with trying to con- duct experiments in space. Although he was never responsible for another instrument, and at first was very neg- ative 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., The Threshold of Space, ed. M. Zelikoff, (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: Springer-Verlag, 1993).

 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 Aeronautics (NACA) and a large contingent from NRL. The latter included most of the NRL Rocket Branch and of those working on Project Vanguard at NRL. The first astronomical activity at 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 accessi- ble from the ground, many astronomers were particularly interested in the UV region. Molecular ozone restricts ground-based observations to the near UV." It was known from studies in the visible that the maximum emission from hot stars is at wavelengths shorter than this ozone limit. Also, the resonance lines of many important light elements and ions such as those of oxygen, aluminum, silicon, carbon, nitrogen, and, particularly, hydrogen are located in the inaccessible region. 18 Although both x-rays and UV emission had been observed from the Sun years before the start of NASA, instruments launched on sound- ing rockets had observed other objects only in the UV. Hence, the early sounding rocket program at 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 pro- gram. 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 develop- ment of several experiments and spacecraft that would become part of NASA's first astronomy satellites, known as the Orbiting Astronomical Observatories (OAOs). [III-4] 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 pro- gram. At that time, the program included all wavelengths—from high-energy gamma rays to long-wave radio waves-for all celestial objects observed from the vicinity of Earth, as well as geodesy.19 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 possi- bilities 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 17. Specifically, it restricts ground-based observations to wavelengths longer than 300 nanometers. A nanometer is 1 x 10º meter. 18. A resonance line is the line absorbed or emitted when an electron moves between the lowest (ground) level and the next higher level. The absorption continuum arises when an electron from the ground level is lost from the atom. The region between the resonance line of hydrogen and the hydrogen continuum is the far UV. 19. 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.

EXPLORING THE UNKNOWN 505 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. 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)-1.20 The OAOs provided a breakthrough with even slightly better pointing than the sounding rockets of that era.[21] Obtaining fine detail from astronomical sources requires good imaging. Astronomers also want to observe a long stretch of a spectrum at the same time. Hence from its astron- omy program's inception, NASA has constantly needed to develop sensitive imaging detectors. In the 1960s, ground-based astronomers used photographic plates for the visi- ble regions, but this procedure was too complex and expensive for astronomical observa- tions from satellites. 22 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 elec- tronic detectors for the different spectral regions. Astronomers also used the photomulti- plier, which had an extensive history in ground-based astronomy. 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 diffi- 20. The OAO program is discussed further in the section of this essay on optical astronomy. 21. It is interesting to note that both systems came to fruition in 1965. Both provided pointing that was 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. 22. The national security community had used films in photo-intelligence satellites and had recovered them.

 cult 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. 23 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-ener- gy 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 astronomi- cal 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 exten- sive access to large, ground-based telescopes and those in the East, who lacked such facil- ities. Astronomers at Princeton, Harvard, and the University of 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 California, in general, thought that the space program was a waste of time and money. 24 Also, many astronomers in 1960 had relatively little background in developing sophisti- cated instruments. The influx of observers trained as experimental physicists solved this problem. With the availability of the IUE in the late 1970s, 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 nat- ural addition to their repertoire, a comfort factor that later increased with the HST.25 Before World War II, most astronomy in the United States had been supported pri- vately. 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 and NASA Administrator T. Keith Glennan signed a memorandum of understanding in 1959 agreeing that NSF should be 23. Although a bare charge-coupled device is sensitive only to the red and near infrared, it can be coat- ed with a phosphor sensitive to other wavelengths or used with another imaging device. Either of these acts as a wavelength converter for the CCD. 24. 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. 25. IUE and HST are discussed in the Optical Astronomy and Great Observatories sections of this essay, respectively.

EXPLORING THE UNKNOWN 507 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 exchanges between the agencies at the program level. [III-9] NASA's interest meant not only access to new techniques in astronomy and the avoid- ance 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. 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.26 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 con- stantly changing budget restrictions continued to rankle. Most investigators also would 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 com- petence of civil service astronomers working for NASA. 27 On the whole, university astronomers felt from the early days of the space agency that NASA was overly bureau- cratic and treated astronomers at NASA Centers preferentially.28 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 commit- tee to advise NASA on the execution of a National Space Astronomy Observatory, among other projects.29 [III-11] The Ramsey Committee's final report suggested that the astron- omy program be transferred to a consortium of universities.30 [III-12] NASA did not accept the suggestion that the astronomy program be run entirely by an outside consor- tium, but attempted to curb the academic scientists' unhappiness with the degree of 26. Research not tied to launch deadlines and comparable in cost to that funded by NSF has been man- aged in much the same way as most NSF efforts, allowing the investigator substantial freedom with little detailed oversight. 27. 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. 28. 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. 29. James Webb to Norman Ramsey, January 14, 1966. 30. NASA Ad Hoc Science Advisory Committee, “Report to the Administrator," August 15, 1966.

 their involvement in program planning by establishing an Astronomy Missions Board, made up of external astronomers, that would advise NASA routinely.[31] [III-14, III-15] Since then, NASA has routinely received advice on its astronomy and astrophysics pro- grams 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 stimulat- ing 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—prob- lems, 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 ques- tions 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 prob- lem, usually under both time and money constraints. While the engineer may experi- ment 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 commu- nicate. 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 inter- preter 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 sev- eral missions, as opposed to developing a unique satellite for each mission. The result has been a compromise. OSOs, OAOs, the Small Astronomical Satellites (SASS), and the High Energy Astronomical Observatories (HEAOs) used the same basic design for 31. NASA Management Instruction 1156.16, "NASA Astronomy Missions Advisory Board," September 25, 1967; ed. Robert Doyle, A Long-Range Program in Space Astronomy: Position Paper of the Astronomy Missions Board (Washington, DC: NASA SP-213, July 1969).

 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 NASA's space astronomy program's inception has been the question of access to the results of observa- tions. In the beginning, the individual investigators responsible for each instrument tend- ed to consider the data proprietary. Moreover, early instrumentation was sufficiently difficult to use and 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 mis- sion'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 rec- ognized, 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. 32 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 instru- ments have been designed that are easier to use, it has become customary 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. 32. 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 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 HST, data are archived quickly in raw form and calibrated “on the fly” when they are requested, although a specified proprietary peri- od may still apply.

 International Cooperation International cooperation has always been an important component of NASA's astrono- my program. Not only do scientists tend to pay less attention to national boundaries than politicians usually do, but NASA also 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 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. 33 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. 34 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 car- ried 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 radi- ation belts. The particles in the Van Allen belts not only present problems for satellite elec- tronics 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. Both the competition for guest observer time and access to the data from all instru- ments always have been open to all competent users, whatever their nationality. In addi- tion, 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. 35 Astronomers from the Massachusetts Institute of 33. 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. 34. Memorandum of Understanding between the United Kingdom and the United States National Aeronautics and Space Administration, November 2, 1970. 35. The VLBI technique links telescopes throughout the world to obtain a resolution equivalent to a tele- scope 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 com- parable 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.

EXPLORING THE UNKNOWN 511 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. As satellites have become more complex, extensive efforts have been made to involve other countries in providing instruments and other spacecraft components. For very expensive missions such as the HST and those currently planned for coming years, shar- ing 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 HST. Europe provided the solar panels and a high-resolution camera on the spacecraft. 36 [III-29] The European Space Agency (ESA) has been included in two pre- dominantly 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 spaceflight program arose once the Apollo program got underway.37 [III-13] The earliest planning for the Large Space Telescope (later to become the Hubble Space Telescope) 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 per- haps 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 wave- lengths 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 possi- bilities of human maintenance, instrument exchange, and recovery for a space-based tele- scope. 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 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 involve- ment in scientific projects. A document that provides great insight into some of this thinking is G. C. Augason, "Manned Space Astronomy," November 1966. 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). 39. Space Science Board, Space Research: Directions for the Future (Washington, DC: National Academy of Sciences, 1966).

 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 sub- stantiated 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 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 spaceflight program, arguing that the developing Space Shuttle would provide rel- atively 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." This change caused significant redesign problems for mis- sions 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 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 experi- mental subjects. When flown, it occupied only part of the Shuttle payload bay. In the addi- tional 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 per- mitted astronaut manipulation of the experiments if desired. Another Spacelab compo- nent, an instrument pointing system, also could 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 observa- tions, it also was 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 dedi- cated to astronomy. The pointing system carried four solar telescopes, and the payload bay

40. NASA, Final Report of the Space Shuttle Payload Planning Working Groups: Astronomy (Washington, DC: 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) Joint Users' Working Group 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, DC: Government Printing Office, July 1975).

 carried a large, hard x-ray telescope on a pallet and a helium-cooled infrared (IR) tele- scope on its own mount. The largest experiment in this payload was a 2300-kilogram cos- mic-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,“ a UV imaging telescope, and a 90-centimeter tele- scope 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 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.“ 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 experi- ments is through the use of Spartan payloads. These are smaller satellites set free from the Shuttle with their own instruments, 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 real- ized 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 astronomers in a number of countries. Smaller experiments have been flown on a Hitchhiker bridge and still smaller experi- ments 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 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 addi- tion, 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 ther- mal, radiation, and atomic environment of near-Earth space. At present, this fact makes 44. A photopolarimeter measures the brightness of an object as a function of the direction of the vibra- tion of the light waves. 45. Only the Copernicus satellite had previously explored the region for which the instrument was opti- mized, and the shorter wavelength region had not been explored at all at that time. 46. The energy contained in each photon ranges from 0.3 to 12 kiloelectron volts (keV).

 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 instru- ments, 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 informa- tion 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 them- selves 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 mea- surements was sufficiently uncertain that confirmation of the line position awaited the results from another balloon flight in 1981. 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 47. The L2 point is a point on the Sun-Earth line, beyond Earth, at which a spacecraft orbits the Sun with- in the same period as Earth and, hence, remains in essentially the same position with respect to Earth. 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.

 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 experi- ment 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.54 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.55 This experiment showed diffuse radiation to be concentrated in the plane of the Milky Way, with a peak intensity in the direction of the center of the galaxy.56 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.5 These bursts often lasted for a number of seconds, with the intensity varying rapidly and chaot- ically in a fraction of a second. 58 There were also a number of x-ray bursts observed with these satellites, but only two were coincident with gamma-ray bursts. These measure- ments 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 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. Eight OSOs, with increasing capability, were eventually flown. Skylab followed in 1973-1974. This human mission produced spectacular results in the x-ray region, the UV, and the visible. 55. 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. 56. Carl E. Fichtel and Jacob I. Trombka, Gamma-ray Astrophysics: A New Insight into the Universe, 2nd ed. (Washington, DC: National Aeronautics and Space Administration, 1997). Some other information in this sec- tion of the essay has also been taken from this book. 57. The bursts had energies in the range 150 keV to 1.5 MeV. 58. J. Terrell et al., “Observation of Two Gamma-ray Bursts by Vela X-ray Detectors," Astrophysical Journal 254 (1982): 279-286.

 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 Milky Way. However, even after thirty years, there is still no understanding of the nature of these bursts. A com- pletely 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, car- ried 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.5 59,60 SAS-2 gave a detailed picture of the diffuse background, which astronomers determined was correlat- ed 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).61 [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. 62 Thus, these obser- vations provide information on both the composition of sources and their physical natures. A team led by W. A. Mahoney observed aluminum in the galaxy.63 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 infor- mation 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. 59. Resolution is extremely important for locating a source. It also helps distinguish a source from the background, which makes it possible to detect fainter sources. High angular resolution is the primary advantage of HST. 60. COS-B, a European satellite launched in 1975, carried an instrument with approximately the same sensitivity and angular resolution. 61. ASA, "HEAO Project Plan," June 13, 1973. 62. 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 the brightness of an entire galaxy for a short time. This outburst is called a supernova because it looks like a nova but is much brighter. 63. W. A. Mahoney, “HEAO-3 Discovery of Al-26 in the Interstellar Medium," Astrophysical Journal 286 (1984): 578-85. Specifically, the team observed the Al-26 line at 1.809 MeV.

EXPLORING THE UNKNOWN 517 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.64 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 Science and Engineering.65 Giacconi had been urged to search for celestial x-ray sources by MIT physi- cist Bruno Rossi, who believed that searching the universe in the x-ray 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 x-ray 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.66 The poor angular resolution of the detectors and the uncertainties in the direc- tion of the sources precluded a closer identification. In addition, the team observed a dif- fuse x-ray background. The following year, Giacconi's group made a proposal to NASA to pursue a program of extra-solar x-ray astronomy studies.67 [III-8] Later rocket observations located these sources more accurately.68 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. 69 OSO-3 observed the hard x-ray diffuse background, and later OSOs also carried x-ray experiments that pro- duced important results, including OSO-8's measurement of iron-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 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." 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 64. 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. 65. Riccardo Giacconi et al., "Evidence for X-rays from Sources outside the Solar System," Physical Review Letters 9 (1962): 439-443. 66. 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 emissions discovered early followed a similar naming scheme. Thus, the first x-ray source discovered was Sco (Scorpio) X-1. 67. American Science and Engineering, "An Experimental Program of Extra-Solar X-ray Astronomy," September 25, 1963. 68. 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. 69. Balloons are still used both to observe hard x-rays and to test new instrumentation for detecting both hard x-rays and gamma rays. 70. The proportional counters were sensitive to the energy range 2 to 20 keV and had angular resolution of one by ten degrees.

 fainter than the Crab Nebula." The final Uhuru catalog contained 339 objects, represent- ing 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." Such sources play a major role in high-energy astronomy. One Uhuru source, Cyg (Cygnus) X-1, later detected opti- cally, 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 satel- lites. Launched in 1972, OAO-3, also called Copernicus, carried small grazing incidence mirrors that fed an x-ray proportional counter. The Astronomical Netherlands Satellite (ANS) carried both x-ray and ultraviolet experiments. OSO-7 and OSO-8 also carried sev- eral 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, 73 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.74 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 detect- ed in the diffuse background, thus confirming the thermal origin of the soft x-ray back- ground 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 provid- ed precise locations for about sixty x-ray sources and a survey of the soft x-ray back- ground.75 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 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 per- mitted 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.76 A catalog of 85 high- 71. Intensities in x-ray astronomy are often given in units of the intensity of the Crab Nebula. This unusu- ally stable object is usually the brightest x-ray source in the sky. 72. This braking radiation results from the conversion of kinetic energy to thermal energy when rapidly moving material is stopped suddenly. 73. A black body is an object that is a perfect absorber of radiation. 74. That is, the radiation came from rapidly moving electrons in a magnetic field. 75. The survey was conducted between 0.1 and 0.28 keV. 76. This was the region between 0.2 and 60 eV.

EXPLORING THE UNKNOWN 519 latitude sources yielded improved x-ray brightness for active galactic nuclei and clusters of galaxies. This experiment showed that all quasars” emit x-rays. Particularly surprising was the detection of 100-second variability in a Seyfert7 galaxy. A catalog of 114 soft x-ray sources also was 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. 79 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.80 The good resolution and imaging capability provided high sensitivity to weak point sources as well as to extended images, such as nebulae. The sensitivity and res- olution 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.[31] During that time, international coopera- tion 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 pro- vided the High Resolution Imager. This mission emphasized softer (less energetic) radia- tion.82 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 mir- rors 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 sen- sitive 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 mystery of the apparent scarcity of these stars after supernova explosions. It has found synchrotron radiation in the outer 77. 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 inter- acting 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 Earth from the Sun. 78. A Seyfert galaxy is an active galaxy with a bright nucleus but is 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 3,000 kilometers. 79. The sources had energies between 0.025 and 10 MeV. 80. 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 pro- portional counter, and a Bragg crystal spectrometer with high spectral resolution. 81. During this time, however, NASA continued to carry out work begun in 1976 on a large x-ray space-craft, the Advanced X-ray Astrophysics Facility, or Chandra, which was launched in 1999. 82. 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.

 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 also can image sources in the x-ray, UV, and visible wavelengths simultaneously. The visi- ble 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. By the 1990s, when NASA became active in launching its own x-ray satellites again, the initial surveys had been essentially completed, except in the extreme UV, and mis- sions were more specialized in their purposes.83 In spite of its name, extreme UV research was more closely related to the x-ray region than to the UV, and normally uses x-ray techniques. Shortward of the edge of the hydrogen continuum,84 the absorption decreases slowly but hydrogen is so abundant that over the large distances between stars, most of the region between 30 and 90 nanometers was expected to be opaque. However, the distribution of neutral hydrogen is not uniform. As a result, in many regions, stars can be seen at moderate distances in some of this wavelength region. Several telescopes on the Shuttle and low-resolution spectrometers on planetary probes proved this. 85 The fields of view on the planetary probes were comparatively large so the instruments were good for observing extended objects such as globular clusters and nebulae.86 The sky background as a function of wavelength in this region also was measured. Although the "telescopes" were small, the long exposure times available on the interplanetary trajec- tories compensated.87 NASA's first satellite dedicated to the extreme UV was the Extreme Ultraviolet Explorer (EUVE). This satellite carried three grazing incidence telescopes.88 Surprisingly, more than twenty extragalactic sources were observed in directions with low hydrogen absorption. All of these sources 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 excel- lent science but because of budget constraints. The Rossi X-ray Timing Explorer (RXTE), launched in 1995, is currently measuring the variability over time, in scales from milliseconds to years, in the emission of x-ray sources in a wide energy range.” Most x-ray sources vary in brightness. The variation in 83. The extreme UV is the region between 0.1 keV and the Lyman break (13.6 eV). 84. The edge of the absorption continuum of hydrogen starts at 90 nanometers, although the crowding of upper level lines causes a pseudo-continuum at somewhat longer wavelengths whose location depends on the spectral resolution. 85. Instruments on Voyager covered the region 50 to 170 nanometers with a resolution near 1.8 nanometers. 86. The fields of view were 0.10 by 0.87 degrees. 87. Much of this paragraph is based on Holberg, “Extreme and Far-Ultraviolet Astronomy from Voyagers 1 and 2," in Yoji Kondo, ed., Observations in Earth Orbit and Beyond (Boston, MA: Kluwer Academic Press, 1990): 49-57. 88. 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 resolu- tion N/A ~300 ($\lambda$ stands for wavelength). Of course, this equation also works for frequency and energy. 89. This included the energy range from two to 250 keV.

 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), and, from a detailed study of a bursting pulsar, provided a stringent test of the way material falls onto a compact object. 90 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 Agency's Great Observatories, this spacecraft is discussed in greater detail below. Optical Astronomy■1 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.92 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 capabili- ty. First, under Office of Naval Research sponsorship, Princeton scientists flew a 30-cen- timeter telescope to observe the Sun. The results were spectacular and proved the advantage of observations above the atmosphere. This success led to the development of a NASA-sup- ported, 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 pos- sibilities 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 focusing on the study of stars and galactic nebulae in the UV. Sounding rockets also were 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 frac- tion 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.■ This technique was then extended to spectra with objec- tive 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 extinc- tion. The astronomers and other technical staff learned how to build 90. QPOs are objects that vary in brightness nearly, but not exactly, regularly. 91. 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. 92. Background sources beyond Earth's vicinity do remain, however. 93. That is, the standard rules governing the behavior of an inflexible body were used to understand the motion of the rocket.

 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 instru- ment at bright stars. And finally, a stable offset pointing system enabled the astronomer to observe anything that his instrument could detect.■4 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 bub- ble on the fuselage with a two-channel photometer providing a visual and a UV band pass. This photometer provided measurements of the sky bright- ness below and above the ozone layer. Martin Burkhead's Ph.D. thesis uti- lized 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 ele- vator 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 spectro- graph on the platform. Observations from the X-15 showed no halos.95 We also obtained the first UV photometry of a late-type star, Antares.■ 94. Theodore Stecher, personal communication. 95. 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. 96. Arthur Code, personal communication.

 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 con- tinuing 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 satel- lite. Four astronomers responded. Code proposed a 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 scientifical- ly interesting proposals, each of these instruments was too large for the small satellite the United States was developing for the IGY. Almost immediately after the establishment of NASA, these proposals were revived. It was clear that the four experiments shared major characteristics. They were comparative- ly 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 instru- ments 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 capa- bility 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 oppo- site 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 experi- ment was incompatible with the same spacecraft design, and thus this experiment was postponed to the Advanced Orbiting Solar Observatory (AOSO), then under discussion.■7 In its place, NASA substituted a low-resolution spectrograph fed by a 91-centimeter mir- ror, 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 to a larger primary mirror, possibly 1.5 meters in diame- ter. The resulting satellites were the OAOs, discussed earlier in this essay.98 [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. 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 97. AOSO was never developed. 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. 98. Homer Newell to Abe Silverstein, “Proposed NASA Project-Orbiting Astronomical Observatories," March 16, 1959, with attachment, March 12, 1959. 99. 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 mainframe com- puters.

 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.[1] 100 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 pro- totype 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 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 con- firmation and more detailed study of the peak in the interstellar opacity near 220 nanome- ters. 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 apprecia- bly 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 experi- ment 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 observa- tion in this spectral region of oxygen that has lost five electrons, Spitzer and his col- leagues determined that much of interstellar space is filled with a hot, ionized medium at about 300,000 Kelvin (K).101 This is not only hotter than many regions of interstellar space, where temperatures are lower than 100 K, but also hotter than the ionized gas near hot stars, whose temperatures reach 10,000 K. Early in the planning for a European space science program, the European Space Research Organisation (ESRO) had proposed an astronomical satellite similar to the OAO and had awarded 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 experi- ment, realized that if the United Kingdom and the United States pooled their planning, 100. For a discussion of the problems OAO encountered, see “The Orbiting Astronomical Observatory," Spacecraft Technology, Vol. VII, ESRO SP-15, October 1966. 101. 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.

 they might be able to amass the funds necessary to build an ultraviolet spectrometer. 102 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 spec- tra 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 chang- ing the order of the program. A second advantage was that in the higher orbit 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. This proposal resulted in the International Ultraviolet Explorer (IUE). 103 Funding came from not only the United States and the United Kingdom, but also from the European Space Agency (ESA), which replaced ESRO in 1975.104 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 available for use by any astronomer with a satisfactory proposal. There were no restric- tions 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. 105 The possibility of obtain- ing observations, in much the same way as ground-based astronomers were used to working, largely overcame astronomers' earlier reluctance to get involved in space astronomy. The sensitivity of IUE's spectrometers was surprisingly high. Not only was it possi- ble to reach the brightest quasars, but a number of fainter ones were also accessible.106 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 spec- tra, the chromospheres[1]07 of cooler stars like the Sun, many types of variable stars, and the nuclei of active galaxies. 108 [III-30] In all, as of August 2000, 3,600 scientific papers had resulted from observations made with this satellite. 109 Because of budget con- straints, IUE was turned off after twenty years of operation, still working well; active use of the data continues. 102. 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. 103. NASA had originally referred to the satellite as SAS-D. 104. Memorandum of Understanding between the European Space Research Organisation and the United States National Aeronautics and Space Administration, March 12, 1974. 105. Yoji Kondo, “The Ultraviolet International Explorer (IUE)," ed. Yoji Kondo, Observations in Earth Orbit and Beyond (Boston, MA: Kluwer Academic Press, 1990), pp. 35-40. fainter. 106. Ibid. The faintest source observed was seven magnitudes fainter than 3C273, i.e., more than 600 times 107. 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. 108. Thomas A. Mutch to NASA Administrator, “IUE Post Launch Report #2," August 16, 1979. 109. Yoji Kondo, personal communication.

526 SPACE-BASED ASTRONOMY AND ASTROPHYSICS NASA's FUSE mission, launched in 1999, investigated the far-UV region. 110 A key question in this region is the ratio of deuterium[11] 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 percent over scales possibly as small as thirty light years. 112 Several decades ago, radio astronomers discovered clouds of neu- tral 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.' The explanation for this combination of neutral hydrogen and highly ionized oxygen is unclear. 113 The most powerful satellite devoted to optical observations is HST. Politically and pos- sibly technically the most complex scientific satellite to date, this spacecraft is one of NASA's Great Observatories and is discussed in detail below. 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.114 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 115 emits 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 K is in the IR. 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. 110. In the 91.2-to-120-nanometer region, the resolution, N/A$\lambda$, is about 30,000; it is more moderate in the remainder of the range. W. Moos, “Lyman and the Far-Ultraviolet Spectroscopic Explorer,” ed. Yoji Kondo, Observations in Earth Orbit and Beyond (Boston, MA: Kluwer Academic Press, 1990), pp. 171-176. 111. 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. 112. M. Lemoine et al., “Deuterium Abundances," New Astronomy Letters 4 (1999): 231-43. 113. W. Moos, "Overview of the Far-Ultraviolet Violet Spectroscopic Explorer," Astrophysical Journal Letters 538 (1999): 1-6. 114. Water vapor and other molecules cause problems in the IR, particularly for wavelengths longer than one micrometer (1 x 106 meter). The atmosphere is opaque in most of the region between 25 and 1000 micrometers. 115. Absolute zero is the temperature at which all atomic motion ceases.

 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.116 The first IR observa- tions of objects other than the Sun were made from a business jet airplane flying at an alti- tude 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 percent in the mid-IR.117 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 1971.118 Among many other results, observations con- firmed that the cosmic background is a black body source at a temperature less than 3 K.119 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. 120 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 oppor- tunities, typically about seventy research flights per year, each 7.5 hours in duration. 121 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 con- structed jointly by Germany and the United States. Airborne instruments are good for studying point and angularly small sources and for 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 116. Balloons are used, particularly, in Antarctica where the air is very cold and dry. 117. H. H-G. Aumann, Airborne Infrared Astronomy (Rice University Ph.D. thesis, 1970), (Ann Arbor, MI: University Microfilms, 1973). 118. F. J. Low, "Airborne Infrared Astronomy: The Early Years," Airborne Astronomy Symposium, NASA Ames Research Center, NASA Conference Publication 2353 (1984): 1-8. 119. 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. 120. As of 1990, the NASA Airborne Observatory Publication list included 789 referenced publications resulting from airborne observations. 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. 121. 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.

 microwave background (CMB) was approximately established from aircraft measure- ments, a detailed study of this background could not be conducted at airplane alti- tudes. 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 CMB. Although there were still problems with the result, Weiss and Muehlner published their observation in the Physical Review in 1973.122 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 pro- duced a catalog of 2,000 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 pro- duced 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. 123 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. 124 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 construc- tion, to both observe fainter sources and obtain more spatial and spectral detail of inter- esting objects. IRAS was unsuited to studying CMB. The Cosmic Background Explorer (COBE), launched in 1989, was a major advance toward addressing 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. 125 This experiment demonstrated that the background radiation is extremely close to that of a black body over a broad range of wavelengths.126 The Differential Microwave Radiometer (DMR) was designed to search for primeval fluctua- ment. 122. Weiss and Muehlner completed their work before Boynton and Stokes had published their measure- 123. The wavelength regions were near 12, 25, 60, and 100 micrometers. 124. 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. 125. FIRAS has two spectrometers with about 5 percent resolution covering the wavelengths 0.1 to 10 mil- limeters. The instrument was cooled to 1.5 K. 126. Specifically, the temperature is 2.726 K +/- 0.010 K.

EXPLORING THE UNKNOWN 529 tions in the brightness of the CMB radiation. 127 The Diffuse Infrared Background Experiment (DIRBE) was designed to study the cosmic IR background. 128 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 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. 129 This satellite was used primarily by guest observers and pro- duced 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, inter- planetary space is also opaque, but there is a region from about thirty to near 500 meters that can be observed from the vicinity of Earth but not satisfactorily from the 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 127. The DMR had three channels in each of three 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 den- sity variations that led to the development of galaxies early in the history of the universe. 128. 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. 129. This range extended from 2.5 to 240 micrometers.

 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 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 resolu- tion. 130 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 mis- sion, the Very Long Baseline Interferometry Space Observatory Program (VSOP). This spacecraft provided one element of a VLBI network. The various ground-based 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 Earth, astronomers were able to obtain higher resolution images of sources such as of the nuclei of active galaxies than those previously available. 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 Earth masks the small effects predicted by Einstein's and newer theories. The possibility of moving away from Earth into a different grav- itation 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 accurate 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 con- firmed by these measurements. 130. 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 diam- eter 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.

 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. 131 Einstein also predicted that a clock runs faster in a strong gravitational field than in a weak field. The gravitational field at 10.5 kilo- meters altitude is still too strong compared to that on the ground to accurately confirm the predicted gravitational effect on clock rate. The desire to confirm the prediction more accu- rately 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 kilome- ters was compared accurately with the frequency of a similar clock on the ground. The fre- quency of the clock downlink was set so that the effects of the ionosphere on the different telemetry uplink and downlink frequencies could be removed. 132 The sum of the delays of both the uplinked and downlinked signals canceled the large correction for the relative veloc- ity 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 the General Theory of Relativity within an accuracy of seventy parts per million. The second- order red shift also matched the prediction of the General Theory of Relativity. These results meaningfully constrain the degree to which competing theories can differ from Einstein's. According to the General Theory of 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 Earth. In addition, there is a small effect on the pointing of the gyroscope (0.05 arcseconds per year) because 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. 133 [III-18] This experiment contains two pairs of cryo- genically 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 gyro- scopes. 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 kilo- meters. A comparison of the readout of the two gyroscopes with the direction of the star can measure the frame dragging and curved field effect. After Fairbanks' death, his col- league, Francis Everitt, took over the development of the experiment. 131. This phenomenon has also been confirmed by the fact that radioactive particles in cosmic rays decay more slowly than they do in a laboratory. 132. Robert Vessot, personal communication. 133. Along the way, there have been a number of technological advancements. One of particular impor- tance to astronomy was the development of the porous plug. This allows the escape of helium gas, formed as liq- uid 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.

 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 increasing 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). 134 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 a 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) The first of the Great Observatories to be launched was HST 135. Even before NASA was created, astronomers had dreamed enthusiastically of orbiting a large space tele- scope (LST). [III-1] As early as 1962, a Space Studies Board (SSB) summer study sug- gested that it was time to start planning of such an instrument. 136 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 compa- nies, partly funded by NASA, began studies of how such a telescope might be launched and controlled. 137 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.' "138 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 134. SIRTF will measure wavelengths almost ten billion times longer than those CGRO measured. 135. 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). 136. Space Science Board, A Review of Space Research (Washington, DC: National Academy of Sciences, 1962). 137. The Boeing Company, "A System Study of a Manned Orbital Telescope." 138. Aden Meinel, personal communication.

EXPLORING THE UNKNOWN 533 Headquarters decided that it was important to start planning for the mission. 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 scien- tific uses of a large space telescope. 139 The Astronomy Program at NASA Headquarters and astronomers on the Astronomy Working Group (an advisory committee that was com- posed of astronomers from both NASA Centers and the non-NASA astronomy communi- ty) began to develop the arguments for such an instrument. In 1970, NASA established two committees: an LST 140 Task Group to map out the engi- neering 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 pri- marily 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 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 leader- ship. 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 con- cept 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 pre- cursor 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 139. Space Science Board, Scientific Uses of the Large Space Telescope (Washington, DC: National Academy of Sciences, 1969). 140. 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.

 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 lob- bying 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 commit- tee 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 succeed- ed 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 like- ly that the Europeans could have successfully bid for fifteen percent 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. NASA's 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 the 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 FY 1977, and no funds specifically for the LST. Again the astro- nomical 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 ref- erences 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 taxpay- er 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 dis- coveries. 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 approximate- ly true. NASA Headquarters directed the Marshall Space Flight Center to 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 origi- nal 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 expan- sion 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 dis- tance, it is only necessary to measure the period of the variation and the mean or max- imum 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 set- tle 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. There was also quieter lobbying behind the scenes. Although there were no astronomers in a high position at NASA, there were several good scientists who understood the objectives of the project. Thus, the first task was to transmit the enthusiasm and wishes of the astronomers with whom NASA was working to NASA man- agers and to get them equally enthusiastic about the project. Next, when they had become enthusiastic, NASA Administrator James Webb, an astute politician, set about relaying that enthusiasm to various groups of politically influential individuals. In the late 1960s, he held a series of dinners for small groups of these people. After each dinner, representa- tives of the Physics and Astronomy Program Office presented the concept of the LST, the design features, its feasibility to the extent that these had been determined, and the sci- entific arguments for the mission. These “dog and pony shows" proved to be very suc- cessful in ultimately gaining political support for the project. Finally, potential contractors began an extensive lobbying campaign well before the astronomers became involved. They also provided significant political guidance to the astronomers as the latter started their campaigns. A new start for the ST was approved at last in the President's FY 1978 budget propos- al. [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 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 prepara- tion 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 intervened 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 com- plex 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 Goddard 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 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 des- perate requests for funds from Marshall, they also tried to squelch the staffing and bud- get growth demanded by STScI. Finally, after a careful look at the functions for which NASA believed 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. 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 pro- duce reduced data from HST, 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 sci- entific 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 high- er is its velocity of recession. A little later, the joy turned to dismay when it was discovered

EXPLORING THE UNKNOWN 537 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 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 sin- gle 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. 141 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 com- pleted and a Shuttle repair mission could be launched. [III-38] In the meantime, mathe- matical methods were developed to get reasonable images from 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 they could point with sufficient accuracy to avoid degrading the image. The problem of improving the determination of the Hubble constant started as soon as possi- ble after the correction of the optics problem. The results to date are still somewhat con- troversial, but most astronomers believe that that the constant is now known within ten percent, in contrast to the fifty percent uncertainty before HST observations. An impres- sive and surprisingly fruitful observation entailed keeping the telescope pointed continu- ously 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 nor- mally 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 uni- verse was only a few percent 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 cen- ters 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. 141. David Leckrone, personal communication.

538 SPACE-BASED ASTRONOMY AND ASTROPHYSICS Compton Gamma Ray Observatory (CGRO) 142 The second Great Observatory was CGRO, launched in 1991. It was named to honor physicist Arthur Holly Compton, who had studied the behavior of gamma rays. This spacecraft also had a somewhat tortuous history. [12] Originally, a somewhat small- er 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 proved to be so expensive that the mission was 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 the HEAO. As all 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. 143 The Burst and Transient Source Experiment (BATSE) was composed of eight gamma-ray modules placed on the spacecraft to provide all-sky coverage.[1] 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 with- in seconds rather than in the two hours that had been planned.145 The Oscillating Scintillation Spectrometer (OSSE) covered the low-energy range." 146 The Compton 142. 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. 143. Together, the instruments covered the energy range from below 0.1 to about 3 x $10^1$ MeV. 144. Each module contains two detectors, one designed for high sensitivity and the other for higher ener- gy 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. 145. 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 sta- tion 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. 146. 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.

EXPLORING THE UNKNOWN 539 Telescope (COMPTEL) was based on Compton scattering. 147 This instrument detected both the energy and the direction of the gamma ray. EGRET covered the high-energy range. 148 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. Originally, a major guest-investigator program was planned for CGRO, but it was not approved due to budget constraints. It was reintroduced when CGRO became part of the Great Observatory program. 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 acci- dent increased the cost of launches sufficiently that this was no longer cost effective. The degree to which the spacecraft could be refurbished in orbit also was 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 reenter 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 inorbit, 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 sci- ence, 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 accomplish- ments: • • • • • • • • • • the finding of new objects including high-energy, gamma-ray blazars (a kind of active galaxy); a very clear separation of the gamma-ray properties of blazars and Seyferts; a major increase in knowledge of gamma-ray bursts; the observation of an increased fraction of pulsar electromagnetic radiation being emitted as gamma rays as pulsars age up to one million years, and the detailed knowledge of their spectra; the determination with high certainty that cosmic rays are galactic; 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; the detection of gamma-ray lines from SN1987A149 and Cas (Cassiopeia) A; the absence of microsecond bursts and its implication for certain unification the- ories; 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 147. 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. 148. EGRET covers the region above 20 MeV. 149. SN1987A is the supernova that occurred in 1987 in the Large Magellanic Cloud, a nearby galaxy.

540 SPACE-BASED ASTRONOMY AND ASTROPHYSICS • 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.15 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 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 Tannenbaum. 151 [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 Earth's radiation belts and in which there would be no temptation to service the mission. The combined weight of the space- craft 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 num- ber 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 calorime- ter on a separate spacecraft; that spacecraft was cancelled in 1993, again because of fund- ing 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 benefited 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 150. Carl E. Fichtel and Jacob I. Trombka, Gamma-ray Astrophysics: A New Insight into the Universe, 2nd ed. (Washington, DC: National Aeronautics and Space Administration, 1997). The information on the CGRO instru- ments is also from this book. 151. Smithsonian Astrophysical Observatory, “Proposal to NASA for the Study of the 1.2-Meter X-ray Telescope National Space Observatory," April 1976.

EXPLORING THE UNKNOWN 541 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. 152 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." 153 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.154 The Infrared Array Camera will use large-area, two-dimensional IR array detectors to provide diffraction-limited angular resolution in the nearer IR.155 The IR Spectrometer will cover the entire range of wavelengths in which SIRTF will be used, with a variety of resolutions and modes. 156 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 space- craft 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 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, cryo- genic technology, and lightweight optics-and the tough funding encouraged very cre- ative thinking on the part of the scientists and the engineers. As a result, the $500 million 152. NASA Marshall Space Flight Center press release, August 22, 2000. 153. Martin Weisskopf, personal communication. Much of the history of the project is also based on this conversation. 154. 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 dis- tributions. It will also use an array detector to provide broad band photometry and mapping from 200 to 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 2,000. Its large collecting area and sensitive array detectors will provide sufficient capabili- ty 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. 155. The telescope will provide diffraction-limited images from 2 to 27 micrometers. 156. The instrument will cover the energy range between 2.5 and 200 micrometers.

 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.” 157 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 1990s "faster, bet- ter, 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 radia- tion, 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 General Theory of Relativity will have been conducted suc- cessfully and another will be far along in development. Plans for the next decade are ambitious. [III-40] They include small missions dedi- cated 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 also will 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 twen- ty 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 pro- ject 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 esti- mate 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 mis- sions 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. 157. Michael Werner, personal communication. Much of the discussion of SIRTF is based on this commu- nication.

EXPLORING THE UNKNOWN 543 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 com- bine 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 mis- sions will be expensive enough, as well as capable enough, so that international coopera- tion 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 col- lecting 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 Earth and its 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 satel- lite in orbit will be linked with ground-based instruments to provide baselines several times longer than the diameter of 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 satel- lites whose separations are accurately measured will look for tiny changes in the separa- tion 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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546 NASA AND PLANETARY EXPLORATION Document III-1 Document title: Lyman Spitzer, Jr., “Astronomical Advantages of an Extra-terrestrial Observatory," Project RAND, July 30, 1946. Source: The RAND Corporation, reprinted with permission. Prior to World War II, Earth-orbiting telescopes only existed in science fiction stories. The advent of guided missiles by Germany during the war, however, made a few astronomers optimistic that this new rocket technology would soon be able to loft telescopes and other astronomical instruments into space. Among the believers, Princeton University's Lyman Spitzer authored a paper for the Douglas Aircraft Company's Project RAND (the think tank established by the Army Air Corps after World War II) on the scientific benefits of a space-based telescope. The paper became part of a larger 1946 RAND report on the feasibility of developing and launching a scientific spacecraft. Originally classified, the Spitzer study was unknown to other astronomers for several years. When his ideas became known, many astronomers remained skeptical of the worth of space-based instruments. Over time, however, astronomers began to embrace the astronomical studies Spitzer described in his paper and eventually attributed the Hubble Space Telescope's development to Spitzer's efforts. [no page number] YALE UNIVERSITY OBSERVATORY PROSPECT AND CANNER STREETS NEW HAVEN 11, CONNECTICUT ASTRONOMICAL ADVANTAGES OF AN EXTRA-TERRESTRIAL OBSERVATORY July 30, 1946. It has been proposed that rockets be used to accelerate a small mass, containing sci- entific equipment, up to a speed of 5 miles a second, at which speed the mass could revolve around the earth indefinitely, forming a small satellite. Such a development is cer- tainly not out of the question within the next few decades, in view of the rapid strides already made in rocket research, and the emphasis now being placed on research in this field. The present memorandum points out, in a very preliminary way, the results that might be expected from astronomical measurements made with such a satellite. The dis- cussion is divided into three parts, corresponding to three different assumptions con- cerning the amount of instrumentation provided. In the first section it is assumed that no telescope is provided; in the second a 10-inch reflector is assumed; in the third section some of the results obtainable with a large reflecting telescope, many feet in diameter, and revolving about the earth above the terrestrial atmosphere, are briefly sketched. It should be emphasized that this is only a preliminary survey of the scientific advan- tages that astronomy might gain from such a development. The many practical problems,

EXPLORING THE UNKNOWN 547 which of course require a detailed solution before such a satellite might become possible, are not considered, although some partial mention is made of certain problems of pure- ly astronomical instrumentation. The discussion of the astronomical results is not intend- ed to be complete, and covers only certain salient features. While a more exhaustive analysis would alter some of the details of the present study, it would probably not change the chief conclusion that such a scientific tool, if practically feasible, could revolutionize astronomical techniques and open up completely new vistas of astronomical research. I. Solar Spectroscopy with a Small Ultra-Violet Spectroscope The simplest astronomical instrumentation for a satellite would be a small spectro- scope, analyzing the ultraviolet radiation which it receives from any portion of the sky; in practice, this would be the solar spectrum whenever the sun was visible. Such a spectro- scope could analyze, either the light incident on a diffuse reflector or the light passing through a small LiF sphere, or bead. Such a system has the advantage that it would not need to be accurately oriented m any particular direction. The intensity in the spectrum could presumably be radioed down to earth. An instrument of this sort would have the fol- lowing uses: [2] 1. Continuous Recording of the Solar Ultra-Violet Spectrum The scientific and military importance of information on the sun's ultraviolet spec- trum has already been pointed out.' Occasional spectra of the sun in the far ultra-violet can presumably be obtained with high altitude rockets which subsequently fall to earth. However, for an adequate picture of the sun's probably large variability in ultra-violet radiation, more frequent measure- ments may be necessary. For a complete examination of the effect which solar distur- bances produce on terrestrial phenomena, especially on conditions in the ionosphere, a relatively continuous portrayal of the sun's output of ultraviolet energy may be required. For example, if a radio fade-out occurs at some particular time, only a record of the solar spectrum during the time immediately preceding can show what the relationship between sun and earth was for that particular fade-out. More important still, for detailed predic- tions of ionosphere conditions, and thus for practical advance information on radio trans- mission conditions, daily measurements of the sun's ultra-violet spectrum are believed to be essential. These can probably be obtained most simply by a satellite observatory. 2. Detailed Analysis of the Earth's Upper Atmosphere As seen from the satellite, the sun will rise and set at frequent intervals. On each such occasion, the sun's ultra-violet light will change markedly as the sun's rays shine through atmospheric layers of changing height. By observing changes of the spectrum with time it would be possible to obtain a detailed picture of how the densities of different types of atoms in the earth's upper atmosphere change with changing height. While essentially similar infor- mation could be obtained from a rocket which rose out of the earth's atmosphere and then fell back to earth, the observations from a satellite could be obtained much more frequently. In view of the probable variability of the ionosphere, resulting from the variability of the sun's ultra-violet radiation, rather frequent spectrographic observations of the structure of the ionosphere, as well as of the sun's ultra-violet spectrum, are probably required to indicate exactly what is happening. It may well be the case that this information can be obtained at less cost with such a satellite than with a series of rockets of lower velocity.

 II. Spectroscopy of the Sun and Stars with a 10-inch Reflecting Telescope To obtain information about the ultra-violet spectrum of [3] the stars, or to analyze in detail the sun's surface as seen in ultra-violet light, a telescope is required, together with means for orienting the instrument in any desired direction. Orientation might be accom- plished in principle by reducing the angular momentum of the satellite to zero by means of external jets; thereafter the satellite could be rotated by internal means to any particu- lar direction, and would point in that direction indefinitely unless hit by a meteorite. Since the telescope would be designed for spectroscopic purposes only, the shape of the mirror would not need to be highly accurate. A 10-inch reflecting satellite telescope, equipped with one or more spectroscopes, would be a powerful astronomical tool. While it would intercept less light than the large reflecting telescopes on earth, it would have the advantage that the background light from the night sky would be much reduced, provided that the satellite was above the atmos- pheric layers responsible for this night illumination; 500 miles should be adequate for this purpose. Thus the faintest star which could be reached with such a telescope might be as faint as that which can just be photographed with the 100-inch telescope, provided that photocell techniques can reach the point where they are as effective as the photographic plate. A photon counting technique, with the use of long "exposures" or, more appropri- ately, "counting intervals" would probably serve this purpose. Such a telescope-spectro- scope combination could measure the spectra of stars, planets, etc., down to at least 1000 A and also out to the infra-red, without the absorption of the earth's atmosphere, which blots out all the ultra-violet and obscures many regions in the infra-red. Listed below are some of the astronomical uses of such an instrument. It may be noted that practical uses of this instrument would not be immediate; this would be an instrument which might be expect to increase very basically our understand- ing of what goes on in the stars and in the spaces between them. Since in this way we obtain information on the behavior of matter under conditions not attainable in the lab- oratory, knowledge of fundamental physics would thereby be enhanced. 1. Detailed Information on Solar Meteorology With a reflecting telescope and accessory equipment, sunspots, prominences, and other types of storms on the sun could be examined in ultra-violet light of different wavelengths. In particular, the behavior of the resonance line of hydrogen (Lyman) at 1216 A would give basic information on the nature of these puzzling and complicated disturbances, which are related to the variability in the output of ultra-violet radiation from the sun. 2. Composition of Planetary Atmospheres The small amount of $O_2$ and $H_2O$ present in the atmosphere of Mars and Venus can- not be detected spectroscopically because of the absorption produced by these same mol- ecules in our own atmosphere. A spectroscopic satellite telescope could observe the spectra of planetary atmospheres without any such interferences, and could supplement observations in the infra-red with equally useful ultra-violet data. [4] 3. Structure of Stellar Atmospheres Among the most abundant elements in typical stars are hydrogen, helium, carbon, nitrogen and oxygen. The absorption lines produced by these atoms in their lowest states (called "resonance lines") all lie in the ultra-violet; the absorption lines of these atoms in the visible spectrum all arise from states whose excitation potential is at least seven volts;

EXPLORING THE UNKNOWN 549 since few atoms are so highly excited, the visible absorption lines produced by these atoms are all very weak, except for hydrogen, whose great abundance makes up for its high exci- tation potential. Thus practically no direct evidence is available on the behavior of heli- um, carbon, nitrogen, or oxygen in most stars. While the resonance lines of helium lie in the far ultra-violet at about 500 A, those of carbon, nitrogen and oxygen all lie between 1000 and 2000 A; the resonance lines of these three elements are unquestionably very strong in the spectra of most stars, and should be readily observable with a satellite spec- troscopic telescope. Such observations should indicate any differences in composition between different stars these differences are important in stellar evolution and stellar energy generation. In addition, the nature of unusual stellar atmospheres - expanding, rapidly rotating, etc. - would be more clearly indicated by information on the behavior of such abundant elements as carbon, nitrogen and oxygen as well as by the behavior of the resonance lines of hydrogen. 4. Color Temperatures of Hot Stars For stars hotter than about 15,000oC, the color of the star, as measured in visible radi- ation, is independent of temperature. Measurements in the ultraviolet would help to determine the surface temperatures of hot stars, a basic item in astrophysical research. 5. Bolometric Magnitudes The determination of the total energy radiated by a star depends on the measurement of the total heat energy reaching the earth from the star; i.e., on the “bolometric magni- tude". For stars whose surface temperature is similar to that of the sun, corrections for infra-red and ultraviolet absorption in the earth's atmosphere are not too serious, but for very cool or very hot stars the result depends heavily on the assumed corrections. Bolometric measurements made on a satellite observatory would give bolometric magni- tudes directly for stars nearby, unobscured by interstellar dust. 6. Analysis of Eclipsing Binaries Much of our present information about the masses, radii and structure of stars has been derived from eclipsing binaries. Measurements in the ultraviolet would be a power- ful new tool in such research. For example, to determine stellar masses it is necessary to observe the Doppler shifts in the lines produced by each of the two stars, and in this way to measure the velocity of each. When the stars are of unequal luminosity this is difficult. However, the less luminous star is frequently smaller and hotter. In ultraviolet radiation the smaller star will frequently be more luminous, and from a satellite observatory its ultraviolet spectrum could be observed, and its velocity thus determined. Changes in the shape of the light curve during eclipse with changing frequency would also give important information on the structure of the atmosphere and on the nature of the opacity of mat- ter in the stars. [5] 7. Absolute Magnitudes and Stellar Distances If the surface temperature of a star is approximately known from its spectrum, its absolute magnitude can be found if its radius can be estimated. Since the surface gravity and resulting pressure decrease together with increasing radius, a measurement of pres- sure suffices to give the absolute magnitude, which in turn gives the distance of the star. Observations of visible stellar spectra have given extremely important results along this line by determining the relative numbers of neutral and ionized atoms, which depend on the pressure. Measurements in the ultraviolet would yield data on the presence of highly ionized atoms, not detectable in visible radiation, and would greatly increase the sensitiv- ity of this method for determining stellar brightnesses and distances. 8. Composition of Interstellar Gas Interstellar atoms and molecules are known to be present between the stars, and to have a total aggregate mass about equal to that of the stars. Such particles are all in their ground state; hence observations of stellar spectra in the visible give no information on the presence of many of the atoms and molecules that may be expected. Measurements in the ultraviolet would give information on the density of interstellar hydrogen in space near the sun, and would indicate how much if any of this material was in the form of molecules. Such mea- surements would also indicate how much carbon, nitrogen and oxygen was present. Detailed information on the nature of interstellar gas may be important in understanding the origin of stars and of cosmic rays, which may both be produced from interstellar matter. 9. Properties of Interstellar Absorbing Grains In addition to atoms and molecules, small grains of matter, about 105 cm. in diame- ter, absorb starlight in space. This absorption, generally important only for distant stars, is greater for shorter wavelengths. The distribution of these grains is known to be very uneven. Measurement of stellar spectra in the ultraviolet should therefore provide a very sensitive indication of the presence of these obscuring particles; comparison of this absorption with that in the visible region of the spectrum should yield information about the composition of these particles, which is an important item in the evolution of inter- stellar matter and in related cosmogonic problems. 10. Nature of Supernovae These exploding stars must be the result of some gigantic cataclysm, possibly a chain reaction involving the entire star. The spectrum of the brighter supernovae is a complete puzzle. Measurements in the ultraviolet would be difficult to obtain with a 10-inch reflec- tor, owing to the great distance and resultant faintness of these objects, but if obtainable might yield an important clue to the nature of the processes involved. [6] III. Astronomical Research with a Large Reflecting Telescope The ultimate objective in the instrumentation of an astronomical satellite would be the provision of a large reflecting telescope, equipped with the various measuring devices necessary for different phases of astronomical research. Telescopes on earth have already reached the limit imposed by the irregular fluctuations in atmospheric refraction, giving rise to “bad seeing". It is doubtful whether a telescope larger than 200 inches would offer any appreciable advantage over the 200-inch instrument. Moreover, problems of flexure become very serious in mounting so large an instrument. Both of these limitations disap- pear in a satellite observatory, and the only limitations on size seem to be the practical ones associated with sending the equipment aloft. While a large reflecting satellite telescope (possibly 200 to 600 inches in diameter) is some years in the future, it is of interest to explore the possibilities of such an instrument. It would in the first place always have the same resolving power, undisturbed by the terres- trial atmosphere. If the figuring of the mirror could be sufficiently accurate, its resolving power would be enormous, and would make it possible to separate two objects only .01" of arc apart (for a mirror 450 inches in diameter); an object on Mars a mile in radius could be clearly recorded at closest opposition while on the moon an object 50 feet across could

EXPLORING THE UNKNOWN 551 be detected with visible radiation. This is at least ten times better than the typical perfor- mance of the best terrestrial telescopes. Moreover, in ultraviolet light the theoretical resolv- ing power would of course be considerably greater; ideally an object 10 feet across could be distinguished on the moon [139] with light of 100 A wavelength. In addition, with such a large light-gathering surface and such low background light, the positions and spectra of stars and galaxies could be analyzed out to much greater distances than is now possible. If the shape of mirror could not be figured so accurately without excessive effort, a large spec- troscopic satellite telescope would still have many important uses. The practical problems of operating such a large installation would of course be enormous. Telemetering back to earth the two-dimensional picture obtainable with such an instrument would involve many problems. With such high angular resolutions, some guiding of the tele- scope might be necessary to correct for changes in the aberration of light during the satellite's orbit. Absorption and radiation of the light received from both sun and earth would require careful consideration to ensure a constant temperature in the mirror and its mounting (to reduce distortion of the mirror's shape by thermal expansion and contraction) and to give a very low temperature in the photo-electric measuring equipment (to reduce the background of thermal emission from the photo-sensitive surface). To provide for a leisurely orbit and thus for relatively constant conditions, such an observatory should preferably be some distance away from the earth, probably as far as telemetering techniques and celestial mechanics might allow. [7] Most astronomical problems could be investigated more rapidly and effectively with such a hypothetical instrument than with present equipment. However, there are many problems which could be investigated only with such a large telescope of very high resolv- ing power. A few of these problems are given in the following partial and tentative list. It should be emphasized, however, that the chief contribution of such a radically new and more powerful instrument would be, not to supplement our present ideas of the universe we live in, but rather to uncover new phenomena not yet imagined, and perhaps to mod- ify profoundly our basic concepts of space and time. 1. Extent of the Universe The 200-inch telescope is designed to push back the frontiers [of] explored space. It is not likely that this instrument will reach to the greatest distance possible. Further mea- surements with the more powerful instrument envisaged here would help answer the questions whether space is curved, whether the universe is finite or infinite. This instru- ment would help in particular to resolve individual stars in a distant galaxy and to analyze their spectra, thus identifying particular stars of known absolute magnitude and in this way determining accurately the distance to the galaxy. At present the distances of most galaxies are known only very approximately. 2. Structure of Galaxies With such great resolving power, such an instrument could explore the details of the structure of galaxies, individual stars could be resolved and the nature of the as yet enig- matic spiral arms could be investigated. Measurement of radial velocities by spectral analy- sis would yield velocities of rotation in a number of galaxies and thus provide direct information about their masses - information now available for only a few galaxies. 3. Structure of Globular Clusters These objects contain so many stars that resolution of individual stars has been possible only for the brighter members. With such great resolving power a much greater percentage of the individual stars could be resolved, some spectra and radial velocities obtained, and a serious attempt made to explore the structure of these stellar aggregations. 4. Nature of Other Planets The controversy as to the presence of intelligent life on Mars could perhaps be settled by measurements with such a giant telescope. Similarly the type of surface detail present on the other planets could be accurately explored with such high resolving power and invariably perfect seeing. Signed Lyman Spitzer, Jr. i. "The Importance High-Altitude Spectroscopy," by L. Goldberg and L. Spitzer, Jr., July 15, 1946. Document III-2 Document title: 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. Source: William Kraushaar, personal collection, reprinted with permission. In the earliest days of NASA's space science program, the National Academy of Science's Space Science Board, and not NASA, attempted to assume responsibility for reviewing and recommending space based scientific experiments proposed by the scientific community for the new space agency to pursue. One such proposal came in 1958 from a team at the Massachusetts Institute of Technology that believed that satellite-based studies of cosmic gamma rays would yield far more precise results than those obtained from balloon-borne experiments, which endured background radiation produced by the atmosphere. Accepted by NASA, the group's gamma-ray experiment flew aboard Explorer 11, launched on April 27, 1961, as the first U.S. satellite devoted to astronomy. [cover sheet] 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

EXPLORING THE UNKNOWN Proposal Submitted: October 10, 1958 553 [no page number] RESEARCH AND BUDGET PROPOSAL FOR THE SUPPORT OF A HIGH-ENERGY GAMMA-RAY SATELLITE EXPERIMENT INTRODUCTION The following is a proposal for research in cosmic rays involving gamma-ray detecting apparatus similar to that which has already been balloon-flown to a very high altitude by the principal investigators of this proposal. The apparatus is clearly adaptable to modifi- cations which will make it suitable for inclusion in a satellite. Funds requested for this work are for a period of eighteen months and in the total amount of $152,000. The need for these funds arises mainly for the purchase of compo- nents and construction materials for four such apparatuses; for funds to be used to cover travel in connection with the experiment; and for an estimated fifty hours of electronic computer time. A comparatively small fraction of the total funds will be used for the salaries of personnel, since it it [sic] intended to carry out the program largely with per- sonnel now engaged in cosmic ray research as members of the laboratory's existing Cosmic Ray Group. [1] I. Introduction PART I SCIENTIFIC PROGRAM High Energy Gamma-Ray Satellite Experiment Somewhat less than a year ago, we at M.I.T. initiated a program to survey the direc- tional intensity of cosmic gamma-rays. Gamma-rays, unlike the proton and heavy nuclei components of the cosmic radiation, are undeflected by terrestrial, solar and galactic mag- netic fields and so should arrive from the direction of their sources. In this sense, gamma- ray astronomy (if the subject ever develops enough to warrant that name) is similar to optical and radio astronomy. Cosmic electromagnetic radiation having frequencies in the optical and radio frequency regions results from atomic phenomena and phenomena which involve the relatively large-scale motion of charged particles. The radiation in the gamma-ray region, on the other hand, should involve distinctly nuclear phenomena, and this fact together with the property of straight-line propagation is what makes the investi- gation seem an attractive one. We shall not discuss here in any detail the various possible sources of cosmic gamma-rays. Generally speaking, two energy regions seem most promising. Gamma- rays in the first region, 0.2 to 5 Mev, should result from the radio-active decay of excit- ed nuclei, fusion of light elements and possibly electron-positron annihilation. Gamma-rays in the second region, 50 to 200 Mev should result from the decay of neu- tral pi mesons produced in either high energy nuclear interactions or possibly in the annihilation of matter and anti-matter. Some sources in these categories have been discussed by Philip Morrison in a recent issue of Nuovo Cimento. In addition to the mechanisms discussed by Morrison, [2] there is an almost certainly present intensity of gamma-rays in the second energy region (50 to 240 Mev) with a very high infor- mation content. To the best of our knowledge cosmic rays exist throughout our galaxy, and should occasionally collide with the nuclei of galactic gas atoms. These nuclear collisions should give rise to gamma-rays through the decay of the produced neutral pi mesons, and the directional intensity of these gamma-rays should yield important information about the cosmic ray and (non stellar) matter distribution in our galaxy. There has been some previous study of gamma-rays in this energy region.", iii, iv Scintillation counters and Geiger Counter detectors of gamma-rays have been carried in ballons [sic], and Geiger counter detectors have been attached to rockets. Even the most significant of these experiments, however, have surveyed but a small portion of the sky with very unspecific solid-angle definition and have suffered from a large atmospherical- ly-produced background. Consequently, only upper limits to the intensity of possible cos- mic gamma-ray intensities are presently available and these upper limits are quite large (a few Mev cm-2 sec[1]). With these factors in mind, and encouraged by the recent possibility of sending large pay loads aloft in balloons, we have designed two gamma-ray experiments both of which are scheduled for flight this summer. The [3] first is sensitive to gamma-rays in the 0.2 to 5 Mev region and includes a scintillation detector with good energy-res- olution surrounded by enough lead to insure reasonable solid-angle definition. The second is sensitive to gamma-rays in the 50 to 200 Mev region and has an angular res- olution of about 0.01 steradian. This equipment is described in somewhat more detail in the next section. The U.S.S.R. delegates to the October, 1957, IGY meeting in Washington, released a number of papers, among which is one by S. N. Vernov, Yu. I. Logachev, A. Ye, Chudakov, Yu. G. Shafer. In this paper they too point out the attractive possibilities of gamma-ray astronomy, and describe a satellite-borne nuclear emulsion experiment. Interestingly, the public press has carried the story that Sputnik III carries gamma ray detection equipment of special significance. II. The High Energy Balloon-Borne Gamma Ray Experiment As mentioned previously, both high and low energy gamma-ray detectors are severely handicapped by atmospherically produced background and to a lesser extent by atmos- pheric absorption even when balloon-borne to heights of 100,000 feet. It is difficult to evaluate without the results of our balloon borne experiments in hand which type of experiment would benefit most by being operated above the atmosphere in an earth satel- lite. Our best guess at present is that the high energy experiment will be the most severe- ly handicapped by the residual atmosphere. Further, there exists in the high-energy region the galactic flux of gamma-rays with a predictable intensity, and while this intensi- ty is probably too small for significant study in a first satellite experiment, the data will be most important in planning future experiments. [4] The accompanying sketch shows the high-energy gamma-ray detector that will be flown late this summer or early this fall. The mercury and lead at the top of the appa- ratus serve as a collimator. Only those gamma-rays with directions more or less along the axis of the apparatus can pass unimpeded between the mercury columns through the plastic anti-coincidence counter and produce electron pairs in the mercury radia- tor. The electron pairs are detected first by the CsI scintillation crystal and then by the lucite Cerenkov detector. The light flashes from these two sources, CsI and Lucite, are detected by a single photomultiplier and distinguished for coincidence purposes by the difference in the characteristic time during which the light is emitted. The Cerenkov detector discriminates against particles incident from beneath, the CsI puls- es are biased for the passage of two minimum ionizing particles, and the large encom- passing anti-coincidence detector insures that incident charged particles will not be recorded. We are certain that there will be present a quite large more-or-less isotropic flux of gamma-rays from neutral mesons produced by cosmic rays in interactions with the nuclei of the residual air above the apparatus, and the heavy shielding is designed to prevent their being recorded when incident from off-axial directions. The solid angle of the collimator is 0.01 steradian when the mercury is in the collimator and is 0. 3 steradian when the mercury is removed. The small solid angle is designed for a study of possible cosmic point sources and the larger solid angle is designed for a gen- eral survey and study of the atmospherically-produced intensity. The solid angle will be changed in flight. The mercury radiator can be removed and reinserted in flight for measurements with and without the radiator providing a convincing test as to whether gamma-rays are really being detected. The apparatus is mounted [5] on a horizontal axis and is programmed to observe the zenith angles appropriate to several possible point sources (Cygnus A, the Sun, the Crab). The azimuth angle is changed continu- ously, one rotation every three minutes. Pertinent data will be recorded photographi- cally and examined following recovery of the apparatus. The total weight of the apparatus including batteries for 20 hours of operation is 500 pounds. III. The Satellite Experiment The balloon-borne high energy gamma-ray apparatus has been described in some detail because the results of this experiment bear directly on the design of the proposed satellite experiment and because it itself is a possible prototype for satellite borne equip- ment. The advantages of satellite over balloon borne gamma-ray experiments are several. The most important is the background question. To be above the atmosphere will not completely eliminate background, for there will still be albedo gamma-rays produced in the earth's atmosphere but travelling up. These will not, however, be coming from the direction of possible cosmic sources. The galaxy, for example, has a maximum thickness of about 0.1 g $cm^2$ looking across the local spiral arm towards the galactic center. A balloon experiment, if the detection of galactic gamma-rays were attempted, would have to distinguish between an intensity proportional to this 0.1 g $cm^2$ in a back- ground proportional to the 10 g $cm^2$ of residual atmosphere. It is safe to say that if the galaxy is at all as we picture it, galactic gamma-rays cannot be studied with balloon borne experiments. The same sort of argument holds true, of course, for other possi- ble low intensity sources. Another important advantage is that the entire celestial sphere can be surveyed from a satellite, while a single balloon-borne experiment can survey at most 10 per cent of the celestial sphere, [6] and an entire survey would require several flights both night and day (or day only if extended over 6 months) every 30 or 40 degrees in latitude. This is because atmospheric background increases as the zenith angle increases and only a band of 25 or 30 degrees in declination can be surveyed from any one latitude. At present we know of no point cosmic gamma-ray sources and even if one or more should be uncovered by the balloon experiment, we wish to propose that a first satellite experiment scan the celestial sphere uniformly. To know where the apparatus is pointed is probably a technical problem far less severe than to actually keep the apparatus point- ed in a given direction. Once source positions are known or suspected, controlled obser- vations will be very important. It should be pointed out that random scanning with an apparatus of solid angle results in an observation time for any particular direction of only T/4 where T is the total available scanning time. For this reason, in the presence of an isotropic noise back- grounds the effective ratio signal-to-noise is independent of the solid angle. This does not mean, however, that the solid angle can be made arbitrarily small, for the detection is inherently a counting process, and statistical significance comes only with large numbers. The optimum solid angle, therefore, depends upon the intensity of the isotropic back- ground, and our best guess at present favors a half-angle of about 10 degrees. The solid angle as well as certain other design features can best be decided when the results of our balloon borne experiments are in hand. In any event, the basic scheme of the balloon experiment seems well suited to a satellite experiment. [7] The following are specific points regarding the feasibility of the experiment. 1. Weight The balloon experiment weights [sic] 500 lbs. including batteries for 20 hours operation and the pressurized gondola. Most of the weight is lead, and in view of the anticipated lower background the weight of the lead can be reduced from 400 to per- haps 200 lbs. With an effective detector area equal to that of the balloon experiment, the weakest point source resolvable will have an intensity of about 5 x 104 $cm^2$ $sec^1$, 10 times smaller than the similar intensity for the balloon experiment. This weakest intensity varies as (J/ AT), where J is the isotropic background, is the solid angle, A is the area and T is the available running time. In the above estimate we have used T=10 days. Since the weight of lead necessary increases somewhat faster than the area, very little is to be gained by say, doubling the weight of lead, and for the first experiment we propose that the effec- tive area be kept near 120 $cm^2$. For reasons of expedience, and the relatively small additional weight involved, some vacuum tubes have been used in the balloon experiment. These can certainly be replaced by transistors, and the total weight of electronic instruments exclusive of telemetering equipment but including power supplies, should not be over 30 pounds. This assumes 40 days of operation and 3 watts dissipated power. Miscellaneous hardware, the scintillators and the radiator will add another 30 lbs, and the total is thus 260 lbs. This is not needless to say, a very precise estimate. 2. Size The balloon borne experiment is within a 37" diameter gondola. A satellite experiment can be made smaller than this because no internal rotations are contemplated. [8] 3. Telemetering With the apparatus as described, coincidence counting rates up to one per second may be expected. Each count must be correlated with the direction (to within a degree or so) of the axis of the detector. This problem, while formidable, does not seem impossible and has probably been considered in connection with other satellite experiments. For proper evaluation of the data it would be convenient to know two or three auxiliary counting rates. These need not be recorded simultane- ously with the principle data, but could if necessary, be telemetered say once every ten earth traversals. 4. Satellite Aspect If left to itself a satellite probably rotates for long periods about a single axis. We, on the other hand, wish to scan the entire sky and, therefore, must pro- vide some method for changing the moments of inertia. This too, it seems likely has been considered in connection with other experiments. Related is the problem of removal. And reinsertion of the mercury radiators for a redistribution of mass is involved. Possibly these two requirements and problems can be arranged to aid each other. 5. Time At least 10 days of actual data seem necessary. Since the axis of the detec- tor will point towards the earth half the time, and since it seems questionable that satel- lite aspect can be extrapolated around the night side of the earth (it has been assumed that aspect will be obtained from the sun) we have allowed 40 days of satellite time for 10 days of useful data. 6. Orbits The orbit requirements are now [sic] severe, except that the apparatus should not enter the region of intense X-radiation reported by Van Allen and his co-work- ers. W. Kraushaar, MIT i. P. Morrison,. Nuovo Cimento, 6, 858 (1958) ii. T. Bergstralh and C. Schroeder, Phys. Rev. 81, 244 (1951); iii. L. Reiffel and G. U. Burgwald, Phys. Rev. 95, 1294 (1954); iv. Rocket Exploration of the Upper Atmosphere, R. Boyd and M. Seaton, editors, London, 1954, p. 306, by C. Johnson, L. Davies, and J. Siry. Document III-3 Document title: Notes from meeting of Dr. J. E. Kupperian and members of the Smithsonian and Harvard College Observatories, January 7, 1959. Source: Fred L. Whipple papers, Archives, Smithsonian Institution, Washington, D.C. Document III-4 Document title: Memorandum to Homer E. Newell, Jr., from Abe Silverstein, “Proposed NASA Project - Orbiting Astronomical Observatories,” March 16, 1959. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C.

558 NASA AND PLANETARY EXPLORATION Document III-5 - Document title: Homer Newell, Deputy Director, Space Flight Programs, NASA, "Memorandum For The Files: Conference Report A Review of the Orbiting Astronomical Observatory Project," February 18, 1960. Source: Fred L. Whipple papers, Archives, Smithsonian Institution, Washington, D.C. Document III-6 Document title: Memorandum to Dr. Nancy Roman from A. D. Code, L. Goldberg, L. Spitzer, and F. L. Whipple, June 15, 1960. Source: Fred L. Whipple papers, Archives, Smithsonian Institution, Washington, D.C. Prior to 1959, no one had ever before attempted to put a telescope into space; a number of leading American astronomers thus found themselves struggling in NASA's early years with precedent-setting scientific, technical, and managerial decisions as they attempted to build up NASA's astronomy pro- gram. Document III-3 reveals that despite the numerous issues that needed to be resolved to make a space-based astronomy mission possible, NASA did not want to ease into space exploration with small, conservative missions, but instead desired to embark on a program of large space observatories. Within the next few months, NASA began planning for a series of astronomical satellites called the Orbiting Astronomical Observatories (OAOs) [Documents III-4 and III-5]. Although, as shown in Document III-6, some of the nation's senior astronomers criticized NASA for its neglect of smaller mis- sions as well as for its management of certain elements of the OAO program, these very astronomers went on to conduct pioneering experiments on the OAOs in a variety of wavelengths. Document III-3 [no page number] The following notes outline the high points of a meeting on 7 January 1959 between Dr. J. E. Kupperian, of NASA, and the Directors and several members of the staffs of Smithsonian and Harvard College Observatories. The notes refer primarily to the meet- ing, in Dr. Whipple's office, attended by Dr. F. L. Whipple, Dr. G. F. Schilling, Dr. C. A. Whitney, Dr. R. E. McCrosky, and Mr. R. J. Davis. NASA has been considering a 1,000-pound "space observatory" project. They are pushing for early 1961 for this. They want to be able to offer the experimenter a "stan- dard" stable platform, perhaps attached to the last stage rocket shell, so that they need only let one contract for the development of the platform and launch vehicle. There is a possibility that this platform would be spinning during launch; the spin to be removed later. They hope to provide for six experiments from such platforms; these experiments will be placed in orbit, no matter how many launching attempts are required, but addi-

 tional experiments will not be added at the end to take care of unused rockets should there be any. It is not entirely certain at present what launching system will be used. However, they plan to have the scientists do science; it will be up to the engineers to sat- isfy them, and the scientist will not have to worry explicitly about launch systems, teleme- try, etc. There will, of course, be much liaison between scientists and engineers. Presumably, an ordinary-looking telescope could be placed on this platform, although, of course, this will probably not be the configuration chosen. The sun is a different problem from the rest of the celestial sphere; the earth is also a specialized problem. It will probably be best not to try to combine solar, terrestrial, and non-solar celestial telescopes. NASA is going to try to avoid a hodgepodge system. There are 2 possible types of fine pointing: a servo loop in the satellite itself, or one going back to the ground. Current thinking on requirements for pointing accuracy and stabilization have the telescope people in mind, since their requirements will probably be most exacting. Other types of experiments will thus have higher stability than minimum requirements. There are three reasons for getting above the atmosphere: elimination of airglow for obser- vations of faint objects; improvement of seeing; getting rid of an absorbing agent that is variable in time, position, and spectral selectivity, and that blocks out some types of information entirely. It is in the third area that NASA expects the most rapid advances, and they therefore are placing the most urgency on developments aimed at this area. They are interested in increasing resolu- tion, for the time being, via balloon experiments; this facet was discussed more thoroughly at lunch. They also want to support a large rocket program, since no experiment should be [2] operated from a satellite if it can be done from a rocket, and since rockets will be nec- essary to provide experimental data on which to base satellite design. NASA wants to start work as soon as possible on actual implementation of these ideas. They are definitely thinking of a quantum jump here, rather than slow devel- opment. Dr. Kupperian has already visited Dr. Goldberg at Michigan; Dr. Spitzer, of Princeton, is now in Washington talking to NASA about this same problem. What they want is a meeting of working scientists and engineers in Washington the first week of February to thrash the whole thing out in both large and small groups, ending up with definite decisions concerning where we should go from the standpoint of experi- ments, hardware and organization. Present thinking is that the experimenter will be Smithsonian-Harvard for one experiment, Princeton for another, Michigan for anoth- er, possibly etc. up to 6, but only Wisconsin was mentioned as an additional party to the February meetings; the experimenter will set the specifications for the experi- ment; NASA will provide engineering and logistic support, including ground stations, perhaps through contractors; the experimenter will have complete control over the operation of his experiment. All of this is still fluid, subject to thrashing out at the February meetings.

 One of the outcomes of the February meetings is hoped to be the instigation of a working group on astrophysical space experiments which will include members of the par- ticipating organizations. NASA wants to have all the problems thoroughly considered before drawing up the actual proposals, so that sending through the proposal will be almost a formality. They want to be able to tell the systems people what is required, and let them take two years to develop it. In this scheme of things, we would have to separate the ground station part of our pro- posal from the rest of it, and submit it separately to the systems people at NASA. The experiments must be kept separate from the systems to work. Glennan himself agrees that the experiment comes first. Experiments must have sci- entific value, not merely publicity value. They want to get the working group together to get an experiment lined up. Thus we would have the plan developed together rather than by the staff at NASA. NASA encourages preliminary experiments in rockets. They hope to provide rocket service for people. They see a service organization to run the ground station network. Mr. Dunkelman, of NASA, has had experience in ultraviolet sensing equipment and systems work (as well as infrared) since 1942. He might be able to help us with industrial liaison. [3] NASA will support projects, but will not support "institutions." They can put out "3-year" money, but cannot promise continuing support (or any support at all, for that matter) to a scientific organization, except in regard to specific projects. Drs. La Gow and Meredith are handling meteor matters. ******** In addition to those at the morning meeting, the following Harvard-Smithsonian sci- entists were at the luncheon meeting: Dr. D. H. Menzel, Dr. J. A. Hynek, Dr. K. C. Henize, Dr. G. de Vancouleurs, Dr. T. E. Sterne, Mr. H. Ingrao, and Mr. G. Nielson. The major new topics of discussion were rocket and balloon astronomy. Notes taken by Mr. Robert J. Davis.

EXPLORING THE UNKNOWN 561 Document III-4 16 March 1959 Abe Silverstein Homer E. Newell, Jr. [no page number] The Office of Space Sciences has completed the initial planning phase of a project for Orbiting Astronomical Observatories, to be launched as part of the National Space Program by the end of 1961. The present planning status of the project is described in the attachment to this memorandum. It is based on staff review, involving the selective adoption and syn- thesis of concepts suggested in preliminary proposals received from interested institutions, and the results of a Space Sciences Discussion Group meeting held on 9-10 February 1959. The preliminary budget estimate totals $57 million, $600,000 of which is to be fund- ed from FY 59 allocations. A breakdown of these figures by fiscal years and major cate- gories is given on page 8 of the attachment. It appears that the projected Vega vehicle system will have adequate capability to perform the mission of this project. [2] Supplementary information: 1. According to agreements reached between Drs. Glennan, Dryden, and Waterman on March 11, 1959, the National Science Foundation will fund and activate, with- in a few days, a proposal by the Association of Universities for Research in Astronomy, Inc. for preliminary studies on the long-range problem of placing a large astronomical telescope in orbit about 1965. 2. Specific proposals for initial studies as part of the research phase of the NASA project described in the attachment have been received from the Smithsonian Institution and Harvard University, and complementary proposals are expected within the next four weeks from the University of Michigan, the Space Sciences Division of the NASA Beltsville Space Center, the University of Wisconsin, and the University of Rochester. These are detailed research project proposals based on the results of the above mentioned Discussion Group meeting. Recommendations It is recommended that the Director of Space Flight Development a. Approve in principle a project of Orbiting Astronomical Observatories as part of the national space program; b. Authorize the Assistant Director for Space Sciences to submit research project pro- posals which constitute initial phases of the Project for early funding of FY 59 alloca- tions, up to a limit of $600,000;

562 NASA AND PLANETARY EXPLORATION c. Authorize the Assistant Director for Space Sciences to proceed with detailed plan- ning, specifications, and improvement of the project. Attachment Bcc: Wyatt Stoller Clark Kupperian Roman Fuhrman Schilling [no page number][attachment] 12 March 1959 Proposed National Aeronautics And Space Administration Project Project Title: Orbiting Astronomical Observatories Project Objective: The objective of this project is to establish and operate astronomi- cal observatories orbiting above the absorbing atmosphere of the earth. Precision tele- scopic observations, with ground control, will be made of the emission and absorption features of the sun, stars, and nebulae in the unexplored ultraviolet, infrared, and X-ray regions of the electromagnetic spectrum. Specific Experimental Objectives: The observing techniques developed for ground based telescopes form the basis of measurements proposed to extend our knowledge into short wave regions of the spectra. The difficulties that will be encountered in detecting and analyzing radiation in the far ultraviolet and X-ray as well as infrared portions of the spectrum dictate quite unique optical and detection systems. This will result in optical and detection systems that are optimized for specific experimental objectives both as to obser- vational technique and wave length region. Some of the proposed observing techniques can be listed: 1. Objective prism spectra a. Stellar spectra b. Nebular spectra and monochromatic images 2. High resolution stellar spectra 3. Broad band stellar photometry [2] 4. Broad band nebular photometry a. Total energy b. High resolution images 5. Monochromatic solar images a. Total solar disk b. High resolution investigations of specific areas of the disk or limb of the sun.

 6. Solar spectra a. Center-limb variations b. Specific areas While some overlap of these techniques can be expected, a single compromise system would have marginal potential. It has developed, however, that a stabilized observing “plat- form" can be constructed which with the addition of the suitable optical and detection sys- tems could support various experimental objectives employing different observing techniques on different flights. Potential Contractors: To date, the following institutions have shown interest in par- ticipating and in instrumenting such an observing "platform": Smithsonian Astrophysical Observatory University of Michigan Observatory University of Wisconsin Observatory Beltsville Space Center (NASA) Space Sciences Division Jet Propulsion Laboratory (NASA) [3] Princeton University Observatory Associated Universities for Research in Astronomy University of Rochester University of California Harvard University Project Scope: The present project schedule includes the orbiting of six astronomical observatories over a period of at least two years. Each would consist of a common vehicle- stabilized platform system instrumented with an optical and detection system optimized for a specific observational objective. This concept is based on considerations of: a) wavelengths region to be covered and observational techniques to be used. b) initial development cost of basic stabilized platform. c) the need for day-to-day programming of telescope. d) capacity of the astronomical community to instrument the platforms, and to recover and analyze the data. e) desirability of exploiting discoveries obtained in the earlier phases of the project. SUPPORT REQUIREMENTS: Research phase: Two areas of endeavor need strong support as a preliminary phase to the orbiting observing programs. First, basic research and product development are need- ed in optical materials and detection systems for use in the ultraviolet, infrared, and X-ray spectral [4] regions. A continued and expanded effort is needed in the study of the inter- action of ultraviolet and X-ray quanta with surfaces, solids and gases. Studies of the pho- toelectric phenomena are needed in all wavelengths since the detectors will encounter large background light levels in the visible and near ultraviolet. Product development will be needed to devise image devices sensitive to selective bands of radiation, and to improve the range and stability of gas ionization detectors currently in use. Additional studies will be needed on the design of the optical equipment to withstand high accelerations and the remote readjustment of the components. Second, rocket borne sky surveys and associated theoretical studies are needed to define the radiation intensity range and the wavelength regions of most promise. While

 the sky surveys are dependent upon future detector development, the present state of the detector art is such that both areas can be vigorously pursued at this time. Past experience would indicate that from 3 to 5 small rocket flights would be desirable in support of each satellite payload. Technological Phase: Of prime importance is the engineering and development of the directable and stabilized mount for the optical system. The basic design criteria nec- essary to support the scientific objectives are: Weight: a. Structure, stabilization and coarse orientation control: 1300 lbs b. Observing equipment (Optics, detection, apparatus, and fine orientation) C. Power supply, telemetering and command functions: 600 lbs 600 lbs [5] Stabilization in orbit: a. Angular drift rates: Drift rates should be less than the libration produced by tidal effects. These should be less than 0.5 degree per orbit. There should be no mov- ing parts after stabilization is accomplished. b. Course aspect: 3 axis control, 0.25 degree steps at 0.5 degree/second. Telemetering: a. Bandwidth - 200 KC band width, suitable for TV type scanning detectors (raster sync pulses could be supplied from ground). Total orbit telemetering is not nec- essary. Command Systems: a. Coarse aspect (3 axis) Fine aspect (3 axis) b. 20 channels of three position controls (up-down-stop) Physical Configuration: a. Capable of accommodating 36" dia. optical element. b. Spherical mass distribution. Departure will cause libration due to the tidal effect of the earth. (See drift rates) Orbit: Perigee: Apogee: Inclination: 500 miles desirable - 300 miles minimum 500 miles desirable - 600 miles maximum 34º Power Requirements and Life: a. Power requirements for experimental equipment: 5 watts average, 50 watts peak for 5 minute intervals during telemetering period. b. Life: 2 years. [6] Vehicle Phase: The projected Vega vehicle system appears to have adequate capability to perform the mission of this project. A nearly circular orbit is desirable. The choice of apogee is such as to be below the Van Allen radiation belt. The choice of perigee depends both upon telemetering considerations and the unstabilizing effect of atmospheric drag. Below about 250 miles, atmospheric absorption would also have undesirable effects. Six Vega vehicles will be required to support the observational phase of the project. About 30 small sounding rocket flights will be required to complete the sky sur- veys and to check detector and guidance systems.

EXPLORING THE UNKNOWN 565 Tracking and Telemetering Phase: Ground stations will serve the dual function of command control and pro- gramming and data recovery. Eighty min. telemetering recovery per day should be allowed. The various experiments will employ somewhat different data acquisition tech- niques. There will be a common requirement for command contact during the satellite pass to maintain the telescope under semi-active control during the teleme- tering period. Active on-board guidance and data storage can be employed in some cases. The ability to reduce the data from successive transmissions and to program the telescope to new regions of the sky will undoubtedly be the criterion in deter- mining ground station coverage. These considerations would seem to limit the requires installations to two or three receiving and control stations. It has been sug- gested that [7] the installation be limited to one master station with slave stations to extend coverage. Management: Project management and technical direction will be provided through the Office of Space Sciences. It is important to note that only after the analysis of the first data obtained from an orbiting observatory is available will its full potential as an astronomical tool be apparent. It can be expected that this analysis will suggest modifications to those sys- tems yet to be flown. Thus, the actual flight schedule will depend some what on this uncertain scientific factor.

566 NASA AND PLANETARY EXPLORATION (2) Support Systems (3) Vehicle Systems [8] PRELIMINARY BUDGET ESTIMATE FOR SIX ORBITING OBSERVATORIES: (1) Research Phase 226 Total $ 6 M FY 1959 FY 1960 FY 1961 FY 1962 0.6 3 .4 $ 8 M 6 $36 M 18 12 (4) Data reduction and Ground Support 7 M 2 2 3 $57 M 0.6 12 29 15.4 REMARKS: (1) Based on participation by 10 research institutions. (2) Assuming use of certain techniques for stabilized platforms developed under NASA Meteorological Satellites and Project Mercury. (3) Based on production costs for 6 vehicles. (4) Assuming use of basic facilities at existing telemetering and tracking stations and full data recovery. Astronomy and Astrophysics Programs Office of Space Sciences March 12, 1959 Document III-5 MEMORANDUM FOR THE FILES SUBJECT: CONFERENCE REPORT A Review of the Orbiting Astronomical Observatory Project - Held 18 February 1960 PARTICIPANTS: Dr. Malcolm Hebbs, General Electric Research Laboratory, Schenectady, New York Mr. Donald F. Ling, Bell Telephone Laboratory Mr. Jesse Mitchell, White House Mr. Homer E. Newell, NASA Dr. Edward M. Purcell, Harvard University Dr. George Rathjens, White House Dr. Nancy Roman, NASA At Dr. Purcell's request, Dr. Newell reviewed broadly the steps leading up to the present time in connection with the Orbiting Astronomical Observatory, and its cur- rent status. He pointed out that the responsibility for this project has been assigned to the Goddard Space Flight Center, and Mr. Ziemer of GSFC has been named project manager. A vehicle has been assigned for the first such observatory, and it is planned

EXPLORING THE UNKNOWN 567 to have some 3 to 6 firings in the course of a two year period following the launching of the first. Dr. Roman then described the details of the planning for the Orbiting Astronomical Observatory. She reviewed the various meetings of the Working Groups, and passes out copies of the preliminary specifications drawn up by the Ames Research Center. Also given out were copies of the information on general specifications handed out to industry, as well as a copy of the minutes of the December 1959 Working Group meeting. The responsibilities of the manager were described. The manner of working with the experimenters was also described, as well as the steps taken to insure that the proper inter- ests of the experimenters were protected. The members of the Purcell Committee were scheduled to meet with Dr. Kupperian at the Goddard Space Flight Center for a presentation on some of the laboratory work to date that has been put in on the Orbiting Astronomical Observatory project. The review of the Orbiting Astronomy Observatory given to Dr. Purcell and his col- leagues was essentially that contained in the attached writeup. Homer E. Newell Deputy Director Space Flight Programs Attachment ******** [no page number] Memorandum for: Hugh L. Dryden Subject: Orbiting Astronomical Observatory 18 February 1960 Jesse Mitchell, Secretary of the Purcell Committee on Space, showed Nancy Roman and me a writeup of the Committee's conclusions concerning the Orbiting Astronomical Observatory based on their deliberations and review of the subject over the last several months. The write- up indicates strong interest of the group in having the Orbiting Astronomical Observatory pushed with vigor and as rapidly as possible. In addition, the writeup indicates dissatisfaction with having only one Atlas-Agena scheduled at the present time for use on this project. The Purcell Committee would like to see perhaps two Atlas-Agenas scheduled for each of three suc- cessive years for this specific project. Finally, the Committee indicated some dissatisfaction with having a NASA group in a position of having to judge between out-house and in-house scien- tific experiments. This point is introduced by stating that there is considerable disagreement on the approach that NASA is taking to the Orbiting Astronomical Observatory project, specifical- ly that the experimenters disagree with having a universally useful and adaptable stabilized plat- form. In exploring into this question, it was brought out that there is indeed a Working Group on Astronomical Observatories in which all of the experimenters are members, that these points have been discussed and considered in the Working Group meetings, and that NASA has carefully taken them all into consideration in arriving at its approach. It was further pointed out that a number of the individual experimenters are obviously interested in controlling the project and directing it to meet primarily their own needs. In the early days of getting going on this activity, Professor Whipple had in a proposal to undertake the management and conduct of the entire job. With this arrangement the proposed satellite would do very well for Professor Whipple's experimental needs, but how it would suit the requirements of other experimenters is open to question. Likewise, Professor Spitzer recently, in a private conversation with Dr. Roman, suggested that the management of the whole [2] Orbiting Astronomical Observatory project be given to him. He said that in this way the needs of Code of Wisconsin and Spitzer of Princeton could be integrated into a single satellite. Dr. Roman inquired as to whether or not this would take care of other interests like the University of Michigan and the Smithsonian Astrophysical Observatory. The answer indicated that this really would not. In fact, what devel- ops is that each astronomer would apparently like to run a specific project on his own cover his needs. This is really not very efficient way of managing the project and is certainly a costly way. The gist of the discussion appears to be that NASA is attempting to manage the pro- ject in such a way as to take care of the requirements of many experimenters in an effi- cient and reasonable fashion, while at the same time not delaying things unreasonably. The experimenters on the working group appear to have been going along with this, but at the present time seem to be seizing upon the opportunity afforded by the new activity of the Purcell Committee to reopen the question. My suspicions are that by so doing, each individual hopes that he himself be given the entire job. We suggested that Drs. Purcell, Roman, and Newell get together to talk over the Orbiting Astronomical Observatories activity and try to come to an understanding of the real problems involved and of the proper way to approach the solution of those problems. Mitchell agreed to arrange such a meeting, which has been done. Homer E. Newell Deputy Director Space Flight Programs cc: Dr. Silverstein [no page number] Document III-6 June 15, 1960 To: Dr. Nancy G. Roman From: A. D. Code, L. Goldberg, L. Spitzer, and F. L. Whipple We are writing this memorandum to put on the record our views on two major items in the NASA astronomy program: first, the vehicles to be used for astronomical observa-

EXPLORING THE UNKNOWN 569 tions in space, and second, the organization of the OAO (Orbiting Astronomical Observatories) program. In summary, we are relatively well satisfied with the proposed organization of the OAO program, but we believe that in addition a strong effort should be made to put smaller astronomical equipment into orbit, at least during the next few years. 1. Vehicles The OAO spacecraft, launched by an Atlas Agena rocket, will make possible a wide variety of astronomical programs in space, and should open new vistas of fascinating and important research. In fact, this equipment might well revolutionize our knowledge of astronomy. To make the fullest use of this powerful equipment, however, it would be very helpful to have preliminary experience with smaller astronomical payloads. Until guided telescopes and their accessory equipment have functioned in space for appreciable peri- ods it will be difficult to design the most efficient and reliable equipment to function in orbit, unmanned, for many months. In addition, some preliminary data on the intensity of stellar radiation in ultraviolet wave length will be of very great importance in designing detection systems to measure this radiation with the large OAO system. The first OAO satellites launched will certainly be much more reliable and useful if some engineering and astronomical data on stellar space astronomy can be obtained beforehand. To some extent such data can be obtained from satellites already launched or sched- uled for the near future, and from rockets. In particular, rockets can obtain limited astro- nomical data on stellar ultraviolet radiation. A guided stellar telescope can be sent up with an Aerobee rocket, and several programs of this sort are now underway. However, a rock- et is above the absorbing layers of the atmosphere for only a few minutes, and the amount of information obtained is strictly limited. According to present plans no stellar telescope will be placed in orbit until the first OAO launching, scheduled for 1963. This would require a very large jump indeed from simple rocket experiments to the massive and sophisticated OAO system. We recommend, therefore, that attempts be made to place smaller, simpler astronomical telescopes in orbit during the next few years. [2] Two possibilities would appear along this line. The first would be to include small astronomical telescopes as secondary equipment in satellites launched for other purpos- es. Wide-band photometry of the brighter stars should be possible [handwritten under- line] in this way. [handwritten note added: if they can be stabilized.] Such equipment would give vastly more information than can be obtained with rockets, and would give important data on the lifetime and reliability of the components that will be used in the OAO program. A second possibility would be to launch small astronomical payloads separately. Development of a separate guided satellite system would appear too costly for such an interim program. However, the S-16 satellite, designed for solar research, could be used for stellar observations. If additional rockets of the Thor-Delta type can be made available for this purpose, it seems likely that a small astronomical satellite could be launched in 1962, well before the first OAO launching, and in time to influence materially the engi- neering and scientific plans for this important program. The early availability of scientif- ic results from the smaller vehicles would also stimulate programs of analysis and interpretation in advance of the launchings of the OAO program.

570 NASA AND PLANETARY EXPLORATION We recommend that the possibility of implementing these two proposals be explored vigorously. 2. Organization of OAO Program In the preliminary document of June 10 a detailed plan for the organization of the OAO program is set forward. We have examined this plan carefully and believe it is reasonable and workable. We have been concerned in the past by the absence of such a specific plan, but our concerns are now largely dissipated by the present document. One area which will doubtless present a continuing problem is the relationship between the experiments and the engineering effort for the OAO. Success of this difficult and important enterprise seems more likely if there is close integration between these two aspects of the program. It is clear from the present plans that the experimenters have no official responsibility for the engineering aspects of the OAO. On the other hand, it is obviously highly desirable that the experimenters have a chance to comment on engi- neering plans when important decisions are being made. Continuing attention to this requirement for integrating engineering and scientific aspects should be given by the var- ious groups concerned, as procedures for carrying out the program gradually develop. [no page number] ADDENDUM It should be pointed out that serious problems of morale and scientific efficiency may arise during a long delay following failure in a major satellite launching. Related programs of lesser scope will provide valuable material to “tide" research groups over such periods. Furthermore, extrapolating from previous astronomical experience, we believe that using smaller and relatively inexpensive satellites will have continuing long-term value for specialized researches suggested by the major program. While the use of smaller vehicles prior to the OAO and possibly on a continuing basis can prove of great benefit, we do feel that the development of such programs should not divert energy or funds in such a manner as to jeopardize either the performance or the time schedule of the Orbiting Astronomical Observatory. Document III-7 Document title: "Memorandum on the Stratoscope II Balloon Project to Assistant Director for Lunar and Planetary Programs," from Morton J. Stoller, Assistant Director for Satellite and Sounding Rocket Programs, November 4, 1960. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C.

EXPLORING THE UNKNOWN 571 In 1946, the Office of Naval Research (ONR) initiated a program of upper atmosphere cosmic radi- ation research from high-altitude plastic balloons. A few years thereafter, Princeton University astronomer Martin Schwarzschild made a proposal to ONR that a telescope be carried in a balloon to photograph the Sun's surface. The success of this project, Stratoscope, led to the sponsorship by ONR, the National Science Foundation, and NASA of a larger, more sophisticated balloon-borne telescope called Stratoscope II. Between 1963 and 1971, Stratoscope II instrumentation observed the atmos- pheres of red giant stars and planets and also obtained high-resolution images of the nuclei of sever- al bright galaxies. [no page number] 4 November 1960 In reply refer to: DG (NGR:sds) MEMORANDUM for Assistant Director for Lunar and Planetary Programs Attn: Mr. R. C. Moore Subject: Support for the Stratoscope II Balloon Project being conducted by Princeton University 1. In mid October Dr. Keller of the National Science Foundation telephoned to inquire whether NASA could provide funding for the Stratoscope II Balloon Project. Princeton University had requested $1,070,000 for this project of which the Office of Naval Research was able to supply $100K and the National Science Foundation $470K. Dr. Keller explained that if NASA could supply $250K, the project could proceed without severe delay. 2. This project is the first serious attempt to obtain high resolution photographs of astronomical objects other than the Sun without the complication of atmospheric seeing. The project is highly thought of in the scientific community and is considered to have the highest priority of any of the projects funded by the National Science Foundation Mathematics, Physics, and Engineering Division. 3. One portion of the astronomy program planned for the Orbiting Astronomical Observatories and their successors is the collection and analysis of high resolution images of astronomical bodies in the visual region of the spectrum. Questions have been raised as to whether it is preferable to do this work from a satellite free from the influences of wind and gravity or from a balloon. Balloons fly at sufficiently high altitudes to permit observations free of most atmospheric turbulence as well as much of the infrared atmos- pheric absorption. Since balloon payloads are recoverable and usually somewhat less expensive than satellite payloads of comparable complexity, appreciable savings can be made in the space program if balloons can [2] provide satisfactory long term observations of this nature. Therefore, the Stratoscope II Project is of direct interest to the NASA astronomy programs. First, it will provide the first attempt to remotely control and operate a high altitude telescope for long period observations of faint celestial bodies and, sec- ondly, it should provide significant answers to the questions as to whether satellites or bal- loons are most efficient for astronomical observations in those regions of the spectrum which can be studied with high altitude balloons. 4. One hundred and twenty five thousand dollars of the money listed in the FY 1961 budget for Satellite and Sounding Rocket Programs under high altitude recoverable astro- nomical experiments can be used for this project. [stamped "Morton J. Stoller"] Morton J. Stoller Assistant Director for Satellite & Sounding Rocket Programs Cc: D/Silverstein DD/Howell NGRoman/sds 3 Nov 1960 Document III-8 Document title: American Science and Engineering, Inc, “Proposal for an Experimental Program of Extra-solar X-ray Astronomy, Prepared for NASA," September 25, 1963. Source: Riccardo Giacconi, personal collection, reprinted with permission. Researchers at American Science and Engineering were the first to detect cosmic x-rays. Encouraged by their discovery, Riccardo Giacconi and Herbert Gursky authored and submitted to NASA in September 1963 a paper describing their vision of a possible x-ray astronomy mission program. Beginning with simple rocket experiments and ending with the launch of a 1.2-meter x-ray observa- tory, the program outlined the ideas that NASA ultimately turned into reality. Their work provided the foundation for missions including the Uhuru satellite launched in 1970 and the Chandra obser- vatory launched in 1999. [cover page] A Proposal for AN EXPERIMENTAL PROGRAM OF EXTRA-SOLAR X-RAY ASTRONOMY

EXPLORING THE UNKNOWN 573 Prepared for National Aeronautics and Space Administration Washington 25, D. C. Prepared by. American Science and Engineering, Inc.. 11 Carleton Street Cambridge 42, Massachusetts 25 September 1963 Approved: [signature] Riccardo Giacconi Vice President Space Research and Systems Division ******** [12] [section] II. REQUIREMENTS FOR FUTURE X-RAY OBSERVATIONS The discovery of galactic X-rays, together with the various hypothesis [sic] that have been put forward to explain them raise two obvious questions which must be answered in future observations: 1. What are the precise position, distances and dimensions of the discrete sources? 2. Do all X-rays come from discrete sources or is there a general diffuse background? A great elaboration of the observational techniques will clearly be required in order to answer these questions and the new ones which will arise in the course of the develop- ment of X-ray astronomy. In common with technical developments for astronomical observations in other regions of the spectrum, those needed for X-ray astronomy will be directed toward: 1. All-sky surveys with increased angular resolution and increased sensitivity to dis- tinguish discrete sources and the diffuse background; 2. Higher resolution studies of the structure of individual sources; 3. Increased spectral resolution both for discrete and diffuse sources: 4. Study of the detailed properties of X-ray emissions such as secular changes and polarization. [13] In view of recent developments in X-ray optics and methods of detection it is now pos- sible to plan along range program of X-ray observations with the assurance that the tech- nical means exist for carrying it out. [14] III. INSTRUMENTATION The instrumentation which is utilized in most of the experiments here proposed is based on two new instruments recently developed at American Science and Engineering, Inc. a photoelectric X-ray detector and an X-ray telescope. These instruments furnish orders of magnitude greater sensitivity and finer angular resolution than the conventional instrumentation.

 1. Photoelectric X-ray Detector The photoelectric X-ray detector utilizes the alkali halides as a photoelectron emitting surface for X-rays in the region between 2 and 100 Å. (Lukirskii 1960). A prototype of the detector has been constructed and tested at American Science and Engineering, Inc. The laboratory tests have confirmed the results of Lukirskii, et al., for $SrF_2$ and have been so promising that this detector was chosen for the OSO-D wheel experiment presently being carried out under NASA Contract NAS 5-3569. The principal advantages of this type of detector with respect to conventional Geiger counters are: 1. The use of extremely thin windows which extends the range of observable soft X-ray wavelengths to the 20 - 100 Å region; 2. The ease of obtaining extremely large detecting areas; [15]3. The relatively low background noise; 4. The extremely long useful life of the device. The detector is described in detail in the ASE proposal ASE-334, “Experiment to Measure Extra-Solar X-Radiation from the Rotating Wheel Section of the OSO-D Satellite". 2. The X-Ray Telescope The X-ray telescope which is proposed for use in phases VI and VII of the proposed research program utilizes the principle of total external reflection of X-radiation at grazing incidence to form X-ray images in the focal place of the device. This instrument was first pro- posed by Giacconi and Rossi in 1960 (Giacconi 1960). It has been developed under NASA sponsorship (NAS 5-660) and is presently utilized on OSO-D for a pointed wheel solar X-ray experiment being carried out by ASE (NAS 5-3569). It is also being used on a pointed rock- et experiment to obtain an X-ray picture of the Sun on recoverable photographic emulsion which is being carried out as a joint ASE-GSFC program (NAS 5-3401). A description of the principle of operation is given in the NASA document X-614-63- 112, "High Resolution (5 arc sec) X-Ray Telescope for Advanced Orbiting Solar Observatory". The principle advantages of using an X-ray telescope are: 1. Large areas of collection; 2. Extremely fine angular resolution (the theoretical limit is a few seconds of arc) coupled to ease of alignment. [16]3. Orders of magnitude improved signal to noise ratio due to the focussing; 4. Ease of construction by use of traditional optical instruments manufacturing tech- niques. [17] IV. THE PROPOSED RESEARCH PROGRAM This program consists of three major steps. First, an all-sky survey is proposed from rock- ets (Phase I), OSO-D (Phase II) and a scanning X-ray satellite (Phase III) which culminates in the detection of sources 100 to 1000 times weaker than presently detected with a resolu- tion of 1 degree and with preliminary spectrum information in the 0.1 to 60 Å region. The second step consists of use of pointing systems to study in detail some of the observed sources or pre-selected potentially interesting objects. Phase N is an experi- ment to be performed by a crew member in the Gemini capsule. Phase V is a non-prime experiment to be performed from OAO. The possibility of pointing permits us to

EXPLORING THE UNKNOWN 575 devote much longer time to the detailed study of single sources than is possible in a scanning experiment. The third step is the introduction of imaging techniques in galactic and extragalactic X-ray observations. Phase VI is a prime experiment from OAO with a 10 foot telescope which will furnish a collecting area of about 38 $cm^2$. An improved version of this experi- ment is Phase VII, where a 30 foot telescope with an area about 400 $cm^2$ is proposed. The angular resolutions which now become possible are of the order of seconds of arc for detailed study of the structure of galactic and extragalactic sources. Even though of necessity the latter phases of the program become less specific, it is believed that the execution of the entire program is well within the state of the art. A pre- liminary time schedule is shown in Figure 2. [18]

576 NASA AND PLANETARY EXPLORATION Document III-9 Document title: Nancy Roman to NASA Associate Administrator for OSSA, “NASA Support of Ground-based Astronomy," March 16, 1965. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. In March of 1959, NASA Administrator T. Keith Glennan and Deputy Administrator Hugh Dryden had reached an agreement with National Science Foundation (NSF) Director Alan Waterman regard- ing a division of responsibility between the two agencies for funding of astronomy research. Under the memorandum of understanding, NSF received authority over ground-based astronomical research, while NASA would fund space-based astronomical studies. Officials from both agencies soon realized the difficulty of making such a strict division work when research efforts often relied on the results of studies conducted both in space and on the ground; NASA thus adopted a policy of funding ground- based research that strongly supported its space program. In 1965, a team led by NASA Astronomy Chief Nancy Grace Roman reviewed this policy in response to a request by the White House Office of Science and Technology that NASA and other Government agencies evaluate a National Academy of Sciences commission's assessment of the needs of ground-based astronomy. Roman's group did not advocate any changes to the policy, but recommended that NASA increase funding to support ground- based astronomy. [1] [stamped "MAR 16 1965"] S/Associate Administrator for Office of Space Science and Applications SG/Chief of Astronomy Physics and Astronomy Programs NASA Support of Ground-based Astronomy The excellent review of the needs of astronomy and astronomers prepared by the National Academy of Sciences committee chaired by Dr. A. E. Whitford has stimulated a detailed re-examination of government support of astronomy. As part of this re-examina- tion, I have discussed the NASA policy on support of ground-based astronomy with the Astronomy Subcommittee of the Space Science Steering Committee and with Drs. Liddel, Brunk, Holloway, Smith, and Mr. Scott. For reference the policy which has been followed within OSSA may be summarized as follows: "General support of astronomy is the province of the National Science Foundation. NASA cooperates with this and other government agencies in an attempt to insure sup-

EXPLORING THE UNKNOWN 577 port of deserving programs and to discourage any possible attempt to stimulate competi- tion between agencies. However, it is obvious that the exploration of space must intimately involve both astronomers and astronomical research. It is difficult to conceive of any area of astronomical research which has no contact with space exploration. Moreover, in many areas of its program, NASA urgently needs additional astronomical research both to plan its programs intelligently and to interpret the results obtained. Therefore, NASA has undertaken the support of both astronomical research and astronomical facilities in those areas of astronomy which most directly affect the space program. In addition it has used the flexibility of its SRT program, its field center research, its training grants, and its facil- ities grants to support, at a lower level, an important broader a of astronomical research from which more closely mission-oriented research must arise." Both groups consulted endorsed the present policy and urged that NASA support of astronomy be enlarged somewhat within the broad guidelines of this policy. They further agreed that, on the whole, the Whitford committee report is well thought out and outlines a program which is well conceived and, at least in optical astronomy, con- servative. However, it is our recommendation that the major responsibility for the [2] implementation of this report lies more appropriately with the National Science Foundation. Within NASA, support of astronomy should remain as it is now, a program activity in OSSA. Program funds should be in-creased to cover a relatively modest increase in support of ground-based astronomy, including research, support of existing observatories, and support of new instruments. A line item in the NASA budget is nei- ther necessary nor desirable. In this context, we have reviewed NASA support of various areas of astronomy, with particular emphasis on the instruments recommended by the Whitford report. We agreed that it is probably not desirable for NASA to take an active part in the design and con- struction of either the largest feasible optical reflector or the largest feasible steerable paraboloid for radio astronomy. These general instruments fall within the traditional province of the National Science Foundation which should continue to retain responsi- bility for them. At the present time NASA has no foreseeable requirement for large opti- cal telescopes in the 150-200 inch class. Funds for the three such instruments recommended by the Whitford paper appear to be available elsewhere. In addition to the telescopes now being built at the University of Arizona and the University of Texas, we foresee the need for major NASA access to two or three additional telescopes of the 60- to 120-inch class in the next few years. We also foresee the desirability of NASA support of at least one or two optical telescopes per year in the 24- to 50-inch class. For tracking satellites and space probes, NASA requires instruments similar to those used for astronomical observations. The instruments should be made available for astro- nomical research on a non-interference basis to the maximum feasible extent as the Baker-Nunn telescopes are now used for flare star photometry and the 85-foot antenna at Rosman is being adapted to radio astronomy. Particularly in the case of the larger instal- lations, such as the 210-foot dishes of the deep space net, the possibility of radio astro- nomical use should be considered in this design stages. NASA is exploring large phased arrays for tracking purposes. The results of researches on such arrays should be made freely available to the astronomical community to direct and support research of mutual benefit to both NASA tracking requirements and radio astronomy.

578 NASA AND PLANETARY EXPLORATION At the present time we do not foresee an obvious programmatic need for NASA to support the other major radio astronomical facilities recommended in the Whitford report. Hence, the responsibility for these [3] facilities should remain with the National Science Foundation. We should undoubtedly continue to support smaller special purpose instruments of particular interest to our programs, as we have in the past supported the low frequency radio astronomy arrays at the University of Maryland and the National Bureau of Standards and the accurate millimeter radio telescope at the University of Texas. It may also be desirable for NASA to support special purpose instruments for the near, intermediate, and far infrared regions of the spectrum. Two areas of ground-based astronomy are conspicuously lacking from the Whitford rec- ommendations. These are radar astronomy and solar astronomy. NASA should continue to partially support the use of existing large radars for special astronomical problems, including both instrumentation directly controlled by NASA and those radars built by other agencies. We do not, at present, foresee NASA support for the construction of new radar facilities, although further experience with radar exploration of the solar system may modify this conclusion. In solar astronomy, specialized, modest scale instruments like coronographs and cinemonochro- mators play a vital role in supporting satellite observations of the sun; two or three additional installations will be required to adequately back up the solar observatories flight program. We also estimate that NASA will want to support about five additional flare patrol photoheli- ographs and at least one intermediate-sized solar tower (telescope and spectrograph). We may wish to provide partial support of the Sacramento Peak vacuum telescope, if necessary, to guar- antee its erection. Some support of other existing facilities may also be desirable. In addition to support of telescope construction, several other areas of ground-based astronomy support merit consideration. NASA should plan to provide a major share of the continuing operational support for those instruments the construction of which we have funded as long as the research conducted is of interest to NASA. We should also increase support of other telescope operations to insure optimum productivity in those areas par- ticularly relevant to the NASA flight missions. This support should include purchase or construction of auxiliary instrumentation, as well as of specific research projects. NASA is in an unusually good position to cooperate in the development of automat- ed instrumentation for ground-based astronomy. NASA has developed many automated techniques for both unmanned observations in space and ground-based reduction of large quantities of data which [4] could be adapted to astronomy. In turn, the further development of such techniques in ground-based astronomy may contribute significantly to NASA's increasing need for automated techniques in data acquisition and reduction As long as NASA is charged with the scientific exploration of space, we shall continue to rely as astronomers both as full time participants in our program or as consultants on special problems. Therefore, we should continue our present policy of supporting astro- nomical education in the following ways: 1. Encouragement of the award of NASA training grants to pre-doctoral astronomy students. 2. Continued use of pre- and postgraduate student assistants on research projects of interest to NASA. 3. Continued support and encouragement of summer institutes for astronomy and related areas.

EXPLORING THE UNKNOWN 579 In summary, we recommend no major change in current NASA policy, but recom- mend an increase in the amount of program funds available to support astronomical research and facilities. cc: SG/Naugle, Smith SL/Brunk, Liddel SC/Holloway, Scott SS/Clark S/Newell SG [signature] John E. Naugle [stamped "16 MAR 1965"] [signature] Nancy G. Roman Document III-10 Document title: "Space Research: Directions for the Future - Report of a Study by the Space Science Board," Woods Hole, Massachusetts, 1965. Source: Space Studies Board, National Research Council, National Academy of Sciences, Washington, D.C. In 1962, the Space Science Board brought scientists together to conduct a major review of recent and future space research. One of the study's most significant outcomes came from the Working Group on Astronomy, which envisioned a large, space-based telescope as the next logical step after the Orbiting Astronomical Observatories. Three years later, when the Space Science Board convened another major review of space research, the Working Group on Optical Astronomy was tasked with assessing the util- ity of large aperture telescopes for optical astronomy. As its members were enthusiastic supporters of space astronomy, the group strongly recommended in the report of the study that NASA develop what they referred to as a Large Orbital Telescope. Soon thereafter, NASA began research on the pointing system for the facility that eventually became the Hubble Space Telescope. [147] [Chapter] II: Optical Astronomy 1. SUMMARY AND RECOMMENDATIONS The Working Group on Optical Astronomy was organized “to examine the future needs of optical astronomy for large-aperture orbiting telescopes of a generation beyond the orbiting astronomical instruments which are now being readied for launching.” The Group interpreted this charge to include the space program for optical astronomy generally, since consideration of large instruments requires study of the scientific data as well as engineering experience gained with small instruments. As applied to the Working Group's area of concern, optical astronomy in space was defined to include all astronom- ical research carried out with reflecting telescopes in space at wavelengths from 800 Å to 1 mm, excluding solar studies. In terms of the instruments used, this definition is logical, since a conventional optical telescope with near-normal-incidence reflecting optics can be used for a wide variety of observational studies in this wavelength range. At the lower wave- length limit, somewhat shorter than 912 Å, mirror reflectivities tend to be low, and stellar radiation is probably completely cut off by the interstellar hydrogen absorption. Above the upper limit of 1 mm, the atmosphere becomes transparent and larger radio telescopes on the Earth's surface are more effective. (Solar research, with different prob-lems of ther- mal control and guidance requirements, needs different types of telescopes from those used for observing stars, stellar systems, nebulae, and planets, and was therefore the sub- ject of study by a different Working Group.) The space astronomy discussions at Woods Hole in 1965 were in some ways a contin- uation of earlier discussions by the Astronomy Working Group at the Iowa Summer Study Group in 1962 ("A Review of Space Research," Publication No. 1079 of the National Academy of Sciences-National Research Council). During the three-year interval since that earlier study, great strides in space technology have been made. Large rocket boost- ers have placed tons of equipment in orbit, and the Gemini flights in the spring of [148] 1965 have shown that man can operate effectively in space, even outside the spacecraft. The progress of optical space astronomy in the study of objects other than the Sun has been impeded by the difficult pointing requirements, but the accumulating data on ultra- violet stellar spectra obtained with sounding rockets (including a recent spectrogram with 1 Å resolution), and the progress made in fabricating and testing Orbiting Astronomical Observatories, suggest that rapid progress in this field can now be expected. The Woods Hole discussions naturally reflect the confidence resulting from these developments. The present report is designed primarily to present the recommendations made by the Working Group, together with enough background material to explain the chief rea- sons underlying each specific recommendation. Many of the auxiliary points discussed by the Group are not mentioned here. To provide general background information, Section 2 presents a brief discussion of some of the most important and striking research objec- tives of astronomy in general and of optical astronomy in space in particular. Section 3 [sections 3-5 not included] discusses the short-range program in optical space astronomy, including flights planned during the next ten years, and related programs in astronomi- cal instrumentation, optical design, and ground-based research generally. Section 4 is devoted to the longer-range goal of a large space telescope. Section 5 comprises three appendixes -- the working papers of the Group. RECOMMENDATIONS The Working Group on Optical Astronomy has considered the possibilities for studying stars, star systems, nebulae, and planets by means of telescopes in space sensi- tive to electromagnetic radiation at wavelengths between 800 Å and 1 mm. For the short- range program (1965-1975), the following recommendations (all summarized here) have been made:

EXPLORING THE UNKNOWN 581 (1) The number of coarse-pointing sounding rockets available each year for optical space astronomy should be increased to twice the present level. (2) Two or more telescopes having apertures of 40 inches or larger should be includ- ed in the Apollo Extension Systems (AES) program. The Orbiting Astronomical Observatory (OAO) program should be continued until AES launchings are def- initely scheduled. (3) Development of various detectors required in space telescopes should be sup- ported by NASA. (4) Development of improved gratings would be of central importance in the space astronomy program. (5) Development of optical interferometers should be pressed, with probable initial operation on the ground. (6) Research and development concerned with problems of space [149] telescope optics, especially with the primary mirror, should be supported by NASA. (7) Support of ground-based astronomy should be increased, as such support is urgently needed for the continuing healthy growth of astronomy in general and of space astronomy in particular. With regard to the long-range program (after 1975), the Working Group has con- cluded that the focus of the national effort in optical space astronomy generally should be toward, and in the context of, a very large orbital telescope to be used with a wide variety of astronomical instrumentation. To help pursue this objective the following recommend-ation (given in full here) was adopted: (8) We conclude that a space telescope of very large diameter, with a resolution corre- sponding to an aperture of at least 120 inches, detecting radiation between 800 Å and 1 mm, and requiring the capability of man in space, is becoming technically feasible and will be uniquely important to the solution of the central astronomical problems of our era. We recommend that the Space Science Board of the National Academy of Sciences appoint an ad hoc panel to work toward this Large Orbital Telescope and to encourage studies of those critical areas where particular research and development is required in the near future to further this program. ******** [162] Infrared telescope. A telescope designed to be diffraction-limited at a wavelength somewhere between 10 and 100 microns might conceivably be made very much larger than an instrument designed for ideal optical performance at 0.5 micron. Until this field of research has been explored more fully from the ground and from space, the value of such a specialized instrument cannot be assessed. Interferometer. The beam interferometer, designed to achieve very high resolution on particular objects, would be a useful instrument in optical astronomy. Current efforts to use this technique from the ground have been discussed above, and further information is required before the need for interferometric equipment in space can be evaluated.

 After study of these various points the Working Group concluded that at present the long-range program in optical astronomy should be concentrated on a single general-pur- pose telescope, though special-purpose instruments might be included at a later date, when and if a clear demonstration of their value can be made. Following considerable discussion the Working Group adopted the following recom- mendation: Recommendation 8 We conclude that a space telescope of very large diameter, with a resolution correspond- ing to an aperture of at least 120 inches, detecting radiation between 800 Å and 1 mm, and requiring the capability of man in space, is becoming technically feasible and will be uniquely important to the solution of the central astronomical problems of our era. We recommend that the Space Science Board of the National Academy of Sciences appoint an ad hoc panel to work toward this Large Orbital Telescope and to encourage studies of those critical areas where particular research and development is required in the near future to further this pro- gram. (See p. 2-21 for considerations leading to the last part of this Recommendation.) Confidence in the technical feasibility of a diffraction-limited 120-inch space tele- scope was based on the various technical studies carried out for NASA directly or indi- rectly by various groups (Boeing, American Optical, Perkin-Elmer); the engineering problems of such a large instrument were discussed only briefly by the Group. The design goal of a 120-inch aperture was adopted in the belief that a long-range instrument should be a very significant advance over the insturements [sic] used in the Stratoscope and OAO programs, whose apertures are in the 30 to 40 inch category. The aperture could well be greater than 120 inches, if that proves technologically feasible (see page 17). [163] It was the conviction of the Group that this large instrument could provide a dra- matic central focus for the optical space astronomy program, and that it would be an appropriate major space program for the nation. It was to help emphasize the central character of this instrument in the national space effort that the name “Large Orbital Telescope" (LOT) was proposed. While the term “orbital” was used for this large-span tele- scope, the possibility of a lunar location was not strongly excluded. Clearly, adoption of the LOT program would have a significant impact on the short- range program in optical space astronomy. While the short-range program discussed in Section 3 is designed primarily to obtain significant scientific results, the data obtained and experience gained would be absolutely essential for the LOT effort. In particular, the AES effort could be an important forerunner of the manned high-resolution LOT. In gen- eral, considerable expansion of much of the short-range program might be required if the LOT were to be effectively used within the time scale outlined below. The subsequent sections discuss the possible design parameters for the Large Orbital Telescope, a time schedule that may be visualized for its construction, and some adminis- trative problems that might be associated with this enterprise. DESIGN PARAMETERS The general characteristics of a large space telescope, discussed in earlier sections of this report, apply to the LOT as well. Thus, this large telescope would be a general-purpose instrument, focusing electromagnetic radiation in the wavelength range from about 800 Å to 1 mm. The Group discussed briefly the engineering problems of this telescope and the design parameters that might be chosen in view both of these problems and of the scientific objectives. While no recommendations were adopted on most of these items, the conclusions are summarized here for reference. Aperture For reasons already outlined, the goal of designing a diffraction-limited 120-inch tele- scope was adopted by the Group. The actual diameter of the instrument would depend, of course, on the technical situation at the time the instrument was designed. One possibility discussed by the Group was that the actual diameter might substantially exceed 120 inch- es, but with the image size corresponding to a diffraction-limited 120-inch mirror. Such an increase in light-gathering power would be desirable for many researches and might be technically feasible if a corresponding decrease [164] in angular image diameter were not required. (If the Saturn V were used to place the LOT in orbit, and the primary were a sin- gle mirror, the diameter could not exceed 250 inches; without doubt, other engineering considerations would limit the diameter to a substantially smaller figure.) Role of Man It was generally agreed that the LOT should be usable for many decades, with occa- sional changes and improvements in the instrumentation provided at the focal plane. This requirement can presumably not be met unless a man is intimately involved in maintain- ing and repairing the equipment, and presumably a man will also be required for the ini- tial adjustment and operation. The design of the LOT should provide for ease in trouble shooting, for access to all parts of the telescope, and for replacement of defective mod- ules. The extent to which a man should actually operate the telescope is a matter of debate, and it is not excluded that the entire system should be completely automated. Guidance on stars will presumably be automatic, and, during this time, man should prob- ably not be coupled to the instrument. However, guidance by man might prove useful for observations of a rotating planet, for which automatic guidance would be difficult. Similarly, in a crowded star field, acquisition of the desired object by a man might be use- ful, though this could be done through use of a television camera rather than by looking through the telescope. There was agreement that the instrument should be completely controllable at will, either by equipment on the ground or by a man nearby. There was some discussion of the likelihood of failures resulting from human error. Location After reviewing the recommendations of the Report on Lunar Exploration Systems after Apollo (LESA, North American, 1965), the Group discussed the relative advantages of the following three different locations for a large space telescope: low orbit (below the Van Allen belts), at 400 km altitude or less; high orbit (above the Van Allen belts), at 30,000 km altitude or more; and on the Moon. Most of the considerations examined would appear to favor the high orbit. As compared with location on the lunar surface, the advantages of a high orbit include no gravitational flexure, no secondary micrometeorites, and lower cost. A possible major disadvantage of the high orbit is greater risk of exposure of equipment and men to high-energy radiation from solar flares, though evidence presented to the Group suggests that adequate shielding is no problem. Objects close to the Sun, however, might be more difficult to observe from a high orbit than from the lunar surface. As com- pared with a low orbit, the advantages of the high orbit are: negligible occultation of objects by the Earth [165] (in a low orbit, occultations complicate the programming and are likely to reduce the net observing time by about one half); nearly constant thermal envi- ronment, which much simplifies the maintenance of the mirror figure; reduction of exter- nal torques due to gravity gradients, magnetic fields, and air drag by at least two orders of magnitude, with resultant simplification of the guidance problem; darker sky than in low orbit, where airglow may contribute light; and virtual absence of oxygen atoms striking the telescope and oxidizing the aluminum. From a high orbit, communication with the ground might be simplified by continuous radio contact, but, as compared with a low orbit, com- munication would be complicated by the increased distance. The greater exposure to solar flare radiation may be an important disadvantage of the high orbit, especially in view of the longer time (at least 10 hours) required to return a human operator to Earth from the high orbit. A very clear disadvantage of a high orbit is that it requires a Saturn V for launching instead of a Saturn IB; since this additional cost would be required for each visit by men, this could be a conclusive argument for the low orbit. The Working Group unanimously came to the conclusion that, on technical grounds, the high orbit appears at the moment to be the optimum location for the LOT. Optical Design A conventional parabola-hyperbola or a Ritchey-Chrétien system seems indicated. The primary should have a relatively low focal ratio to minimize the over-all length of the instrument. Use of the prime or Newtonian focus would not seem to offer any particular advantages, and all of the instrumentation would presumably be at the Cassegrain focus, possibly with tiltable mirrors to direct the light toward the desired instrument or sensor. Careful baffling would be required to keep earthlight as well as sunlight out of the opti- cal path, and the secondary supports should presumably be apodized (with Couder strips). Automatic focusing would presumably be required and, probably, automatic col- limation as well. [167] ADMINISTRATIVE PROBLEMS Three different phases of the program were considered: (a) preliminary phase, (b) design and construction, and (c) post-launch operation. As entirely different adminis- trative problems would be encountered in each of these phases, they are discussed sep- arately here. Preliminary phase Such a major astronomical effort as the LOT should not be undertaken until a major- ity of the astronomical community supports the program with enthusiasm. It appears to the Working Group that progress in space research generally, and in space astronomy par- ticularly, combined with increasing awareness of the close interdependence of space astronomy and ground-based astronomy, may help in generating enthusiasm for the LOT among U.S. astronomers.

EXPLORING THE UNKNOWN 585 To help in explaining LOT plans to their colleagues, and in pressing for the program generally, the Working Group concluded in effect that the Group as a whole, or a repre- sentative fraction of it, should continue in existence, as an ad hoc panel, and requested the National Academy of [168] Sciences to endorse a proposal to this end as contained in Recommendation 8, page 3. The purpose of the panel would be: (i) To attempt to broaden the base of support, for (a) the space astronomy program in general, and for (b) an eventual launching of a large astronomical instrument in par- ticular. By discussion with their colleagues, they would hope to clarify the issues involved and to stimulate the interest of astronomers who are at present unfamiliar with the aims of the space program. (ii) To begin an orderly examination of some of the technical problems that will arise in the design of a large orbiting telescope, anticipating that more permanent arrange- ments will be made later. (iii) To implement these two aims by holding fairly frequent informal meetings, preparing discussions of specific subjects, inviting the participation of other astronomers, and generally to keep alive the idea of working toward a large orbital telescope. Design and construction phase In the initial organization of the program and during all successive stages until launch, there must be close and effective contact between NASA and its engineering contractors, on the one hand, and the astronomical community on the other. How this contact can best be maintained and integrated into the vast administrative structure required for such a large program is a question that deserves careful study. Perhaps a group of astronomers might be organized to carry out detailed design studies, with advice from engineers and optical experts; such a group might then serve in an advisory capacity during the engineering design phase that would follow. Perhaps a committee under the National Academy of Sciences, with representatives from various interested groups, might serve a useful function in this context, and might help to provide a bridge between the NASA organization for the LOT and the. sci- entific community. Further exploration of these and other possibilities is desirable. Operations phase Clearly, the LOT would be a truly national facility, and should be administered as one. The plan should be workable from the standpoint of NASA's internal administration, since the sit- uation would be complicated by the fact that flights would be involved. The Working Group visualizes that the detailed program for operating the LOT (allotment of observing time, expe- ditious recovery of data, proposals to place auxiliary instruments of newer design on board, etc.) would need to be managed in a way analogous to present ground-based national facili- ties. Responsibility for detailed scheduling must be defined, as it would depend not only on the scientific [169] program but also on such factors as the relative position of the telescope, the Earth, the Sun, the object to be observed, communications, etc. Experience with the OAO- D program, in which two-thirds of the observing time will be allotted to guest investigators (i.e., investigators other than the principal investigator, who is responsible for the experiment), may help to reveal some of the administrative problems in these areas.

586 NASA AND PLANETARY EXPLORATION Document III-11 Document title: Letter to Dr. Norman F. Ramsey, Harvard University, from James Webb, Administrator, NASA, January 14, 1966. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Document III-12 Document title: NASA Ad Hoc Science Advisory Committee, “Report to the Administrator," August 15, 1966. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. In January 1966, NASA Administrator James Webb sent a letter to Norman Ramsey of Harvard University requesting that he head an ad hoc committee to recommend how NASA ought to pro- ceed on a variety of space science activities, including the ways in which NASA could involve the academic community. Among its tasks, the committee was asked to provide advice on how NASA should develop and manage a major space observatory project that the National Academy of Sciences' Space Science Board had proposed the prior summer. The Ramsey committee's response to NASA's request regarding the space observatory focused largely on the management of such a facility. In particular, the committee strongly endorsed the concept that a consortium of universities, which it called the Space Telescopes for Astronomical Research, Inc., or STAR, be established and charged by NASA to select and manage the scientific investigations that would be conducted on the space observatory. Although NASA was reluctant to give so much authori- ty to an external group so quickly, the space agency did establish an astronomy advisory group made up of non-NASA scientists, and ultimately awarded management of the Hubble Space Telescope's scientific operations to a non-NASA entity. [1] Document III-11 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON. D.C. 20546 January 14, 1966

EXPLORING THE UNKNOWN 587 OFFICE OF THE ADMINISTRATOR Dr. Norman F. Ramsey Harvard University Cambridge, Massachusetts Dear Dr. Ramsey: The purpose of this letter is to request you to assemble and chair an Ad Hoc Science Advisory Committee to advise NASA in the execution or [to ascertain] the major new pro- jects which are either underway or under serious consideration within the agency. These projects are the Voyager/Automated Biological Laboratory Program, the post-Apollo lunar exploration program, and the National Space Astronomy Observatories recom- mended by the Woods Hole Summer Study. As you are well aware, the objectives of those large complex programs have been devel- oped through an intensive interaction with the scientific community and, I believe, are well accepted by that community. The objectives and goals of Voyager have been reviewed by the President's Science Advisory Committee, so you are well aware of the aims of that Program. In view of the interaction which has taken place with the scientific community, you may question the need for further consultation and work on the part of people such as yourself and the others we would like to see on the advisory group. The need for such a group arises from the problems involving the scientific community due to the size, [2] complexity, and long lead time of these projects. In the past, scientists at universities and Government laboratories have been able to participate directly in the program by conceiving, designing, and building their own experimental apparatus, which was then inte- grated into a spacecraft and flown. After the flight, the scientist received the data and was able to analyze the data and publish the results in the established tradition of academic research. We in NASA think it is essential that competent scientists at academic institutions par- ticipate fully in the next generation of space projects, and we believe that we will need new policies and procedures and perhaps new organizational arrangements in order to enable them to participate. The next generation of space astronomy projects is an example of some of the problems we face. The astronomers at Woods Hole recommended that NASA develop 120-inch tele- scopes for space astronomy. We envision such an instrument as a National Astronomical Observatory in Space – an astronomical facility in space for astronomers to use, rather than the separate instruments developed by individual scientists such as we have on the Orbiting Astronomical Observatory. We estimate that it will require at least a decade to bring such a facility into being. During that period NASA will have to work closely with many of the most competent astronomers in the country. We have a nucleus of competent astronomers and engineers at the Goddard Space Flight Center; however, we expect that nucleus will have to be strengthened. It is exceedingly important that we have highly competent scientists and engineers at the Center responsible for a major astronomical facility and that we have the proper kinds of people in positions of leadership at the Center. [3] As another example, it would appear that the Automated Biological Laboratory (ABL) will have to be a “laboratory" to be used by scientists, rather than a "collection" of individual experiments designed and built at several institutions. The requirements for sterilization and the severe constraints on weight imposed by the low surface pressure on Mars dictates that the ABL must be a tightly integrated package, designed and built under the most exacting conditions in complex facilities which will be too expensive to dupli- cate. However, the most competent biologists and physicists in the country must be deeply involved in the conception, design, fabrication, and testing of ABL to assure the success of the mission. Furthermore, this must be a continuing involvement over a period of six to eight years prior to launch. Obviously, great care must be taken in the assignment of responsibility for ABL and the selection of key personnel to design and build it, so that competent scientists will want to participate in the development and proper relationships can be established with scientists at academic institutions. Clearly, one of the major tasks of this advisory group would be to review the resources at our NASA field centers, and such other institutions as would be appropriate, against the requirements of the next generation of space projects and advise NASA on a number of key problems, such as: (1) How can we organize these major projects so that the most competent scientists and engineers can participate? (2) How can academic personnel participate and at the same time continue in strong academic roles? (3) What mechanism should be used to determine the scientific investigations which should be conducted? [4] (4) How does a scientist continue his career development during the six to eight years it requires to develop an ABL or a large astronomical facility? (5) Should we change the orientation of some of our NASA Centers? (6) What steps should be taken in scientific staffing, both inside and outside NASA, over the next few years to assure that we have the proper people at the proper places to do the job? (7) How can we obtain the competent scientists to take the key roles in these major projects? If you will undertake this job, we at NASA will work closely with you. Dr. Newell and the staff of the Office of Space Science and Applications will arrange any briefings which you desire, and will arrange for tours of the NASA Centers. We envision a group of astronomers, biologists, physicists, and geologists from both departments and administration in the universities. NASA would provide per diem and would pay the usual consulting fee. I will be glad to meet with you and discuss this further at your convenience. Sincerely yours, [signature] James E. Webb Administrator

[i] EXPLORING THE UNKNOWN 589 Document III-12 [cover letter] HARVARD UNIVERSITY DEPARTMENT OF PHYSICS LYMAN LABORATORY OF PHYSICS CAMBRIDGE, MASSACHUSETTS 02138 August 26, 1966 Mr. James Webb, Administrator National Aeronautics and Space Administration Washington, D. C. 20546 Dear Mr. Webb: The Ad Hoc Science Advisory Committee, which you asked me to assemble and Chair in your letter of January 14, 1966, has convened a series of meetings since that time and has prepared its recommendations. The Committee in its deliberations has been greatly assisted by members of the NASA staff, by participants in the NASA program, and by other individuals. The Committee herewith forwards its report. We believe that the changing nature of the National Space Program will create a multitude of new and deep questions of science, administration, and management. We have, therefore, made a number of recommenda- tions to help you in meeting these anticipated new problems. Please feel free to call on us if we can be of any assistance to you in the interpretation of these recommendations. Sincerely yours, [signature] Norman F. Ramsey, Chairman Ad Hoc Science Advisory Committee National Aeronautics and Space Administration ******** [17] G. Large Astronomical Facilities in Space Clearly, if NASA is to engage in a scientifically orderly development of a large earth- orbiting astronomical facility, which is a long-term undertaking of great cost, NASA needs the assurance of a continuing, responsible commitment from the scientific community towards this endeavor. Reciprocally, in view of the long-term character of this commit- ment, the scientific community needs the assurance of a reasonably strong role in the sci-

 entific direction of the program. The following plan suggests a mechanism to fulfill these two needs. Let us assume that the general plan of building a large multi-purpose space astro- nomical facility has preliminary approval, and then attempt to envision the various steps toward an orderly organization of the task. A legally constituted organization of universi- ties active or interested in the fields of optical, radio, X-ray, gamma-ray astronomy and other terrestrial radiations can be used. The Board of Trustees of this organization can appoint consultants who are representative of other interested persons and related research fields. The organization should be primarily designed to achieve the following: 1. A long-term commitment of the astronomical community, solidly based on insti- tutional commitments of a representative group of universities, to assist to the fullest extent required in the planning, design, construction, and use of an orbit- ing astronomical facility. 2. A means whereby leading astronomers can provide the necessary scientific direc- tion in the creation and use of the facility, while still preserving their university roles in research and education. [18]3. A means for securing international participation in the creation and use of the facility. The facility will take many years to build, and it should operate for a very long time-ground-based telescopes 60 years old still produce useful research. We conceive of the facility as a number of scientific instruments, most of them under common operational control, relatively closely grouped around a space station in an approxi- mately 200-mile orbit, so their scientific re-supply and engineering access is possible and economical. Earlier astronomical telescopes, including OAO, OSO, X-ray and other newer high-resolution telescopes, will provide essential, preliminary and con- tinuing experience. The corporate entity would provide continuity of scientific planning, instrumenta- tion, research and development, and programming. The function of this organization can be fulfilled either by an existing not-for-profit interuniversity corporation, or by a new one. In either case we shall, for convenience here, call the organization Space Telescopes for Astronomical Research, Inc., or STAR for brevity. STAR would obtain the best and most authoritative advice from the scientific community in defining the goals of the sci- entific program, and the details of the instruments that would become part of the scien- tific facility in space. STAR would develop preliminary specifications that would be transmitted to NASA Headquarters, which in turn would direct the appropriate field Centers to prepare alternative and competing designs and engineering approaches. Rival simultaneous and separated approaches in this phase seem desirable, considering the complexity of the problem; any apparent waste of manpower and time in this preparato- ry phase would be small compared to that in constructing and launching inefficient devices, because of the high costs of orbiting large payloads. A first-phase report prepared by STAR should be transmitted to NASA, and it should give the major scientific goals, con- clusions on [19] feasibility, and studies to indicate costs. STAR would work closely with NASA Headquarters, the NASA Centers, and the industrial designers to evaluate the designs and conduct trade-off studies.

 In phase two, let us assume that either one or more of the NASA Centers is assigned the management of the large astronomical facility. Its major instruments may include a large optical telescope, special -purpose solar telescopes, high-frequency radio telescopes, X-ray and gamma-ray telescopes, other radiation detectors, and possibly an associated space station. STAR would have an administrative, planning and small scientific staff at its headquar- ters. The Advisory Board of STAR would report its operations both to the member universi- ties and to NASA at a high level. In return, the STAR Board would be kept informed by NASA as to the direction the program is taking. STAR would also provide to the chosen NASA Centers continued scientific review. Because of the enormous complexity of the sci- entific and engineering problems involved, a close liaison must be maintained between NASA Headquarters, NASA Centers, and the engineering groups, contractors, and scientists in STAR. Although a NASA Center would be responsible for the construction of the major elements of the facility, certain sub-systems and scientific auxiliaries could be designed and built most efficiently by STAR, or by individual universities or scientists. The relative permanence of the principal elements of the facility places a heavy bur- den on its planning because further developments of astrophysical knowledge will affect the scientific goals. Maintaining continued close relations between the management Center and the university community will help to provide the most fruitful multi-purpose large astronomical facility. Above all, the design should be kept responsive to the scientif- ic goals, not only during the planning phases, [20] but also as late as possible during con- struction; also great care must be taken to ensure that the demands of engineering do not unduly compromise these goals. The sequence of devices to be built for X-ray astronomy will depend largely upon the present rapid advances in this field, and they will be better defined as observation and technology advances. Gamma ray astronomy, now in an early stage of growth, can also be integrated into the orbiting facility. A submillimeter or millimeter wave length radio antenna may be in the same orbit if scientifically justified, but a much higher orbit is required for a very low frequency, large radio telescope. Although physically separate, the latter, organizationally, belongs within the facility and STAR organization. Likewise, the STAR organization may be involved in providing the smaller orbiting telescopes that pre- cede the large one. The large orbiting astronomical facility will involve manned attendance with much hardware already available, possibly from the Apollo program, for re-supply, updating of sensors, repairs of defective modular subsystems, and recovery of photographic material. This is an essential operational feature because of the great cost of the large telescopes. The involvement of man would permit flexibility for future changes in the scientific pro- gram, would provide a closer link for cooperation between scientists and those interested in the continued development of our national capability for man-in-space, and would famil- iarize man with the problems of operating elaborate scientific devices under less difficult conditions than are normal in the smaller space vehicles of two or three man capacity. For the operational phase STAR would develop policy for allocating telescope observ- ing time to scientists from STAR, other universities, Government laboratories, NASA Centers, ground-based observatories, and to other interested scientists. The scientific pro- gram and definition of the operation policy of the telescopes, [21] including changes of subsystems, would be under the direction of the Board of STAR. Operational control of the facility, including engineering, re-supply, and safety, would be the responsibility of the NASA Centers. Astronomy has traditionally been a field that excites the imagination and interest of a wide variety of inquiring minds, and one in which there is a long history of fruitful inter- national cooperation. The nature of the orbiting observatory is such that participation in the scientific use and program of observations could form an interesting and natural basis for international cooperation and for providing a powerful and constant reminder of the genuine interest of the United States in learning how to engage in helpful international cooperation. It would hence be very valuable to make clear from the beginning that this unique facility, the orbiting observatory, is intended to serve astronomers on a world-wide basis, and to work out meaningful ways in which the world's most creative astronomers could participate and contribute to the scientific program. The extent or mechanisms through which international representatives should be involved in the management and planning of the observatory have not been examined. However, we believe that STAR could facili- tate the working out and operation of appropriate arrangements. Document III-13 Document title: G. C. Augason, "Manned Space Astronomy," NASA Headquarters, November 1966. Source: Space Telescope History Project, Archives, Smithsonian Institution, Washington, D.C. NASA's emphasis on human space flight in the 1960s affected nearly all of its activities, including the astronomy program. For example, Boeing's 1965 feasibility study for NASA on the Large Space Telescope the first extensive NASA-funded study on what became the Hubble Space Telescope— assumed that the observatory would be supported in various ways by human inhabitants of a near- by space station. Many other studies likewise considered the possibility of using humans in space to service or operate astronomical facilities. This NASA overview highlights many of these studies. [cover sheet] MANNED SPACE ASTRONOMY G.C. AUGASON NASA HEADQUARTERS NOVEMBER 1966

[no page number] EXPLORING THE UNKNOWN 593 MANNED SPACE ASTRONOMY SECTION I – EARLY EFFORTS Astronomy Subcommittee The purpose of this review is to recount the efforts made by the National Aeronautics and Space Administration (NASA) to use man in space as an aid in astronomical research. The Astronomy Subcommittee of the Space Science Steering Committee (SSSC) early anticipated the importance to astronomy of man in space. At the second meeting of the Astronomy Subcommittee, May 23-24, 1960, the role of man was discussed. J. A. O'Keefe was given the assignment of determining the effect of motion by the astronaut on observations. He reported in a later meeting that it was possi- ble for the astronaut to guide on objects which were several minutes of arc in angular sub- tense. At the fourth meeting, October 24-25, 1960, the fact that an astronaut could make useful observations was once again emphasized and it was stated that astronomical train- ing of the astronaut would be worthwhile. At the October 30-31, 1961, meeting an Ad Hoc Committee for Scientific Tasks for Man-in-Space was formed under the chairmanship of Dr. Jocelyn Gill. One of the tasks of the new committee was to develop a training program that would help the astronaut to make meaningful astronomical observations. [2] On February 20, 1962, the United States accomplished its first orbital launch when John Glenn made a three-orbit flight in the Mercury capsule, Friendship 7 (MA-6). In addition to his assigned tasks, Glenn made several observations which were of astronomi- cal interest. At the subcommittee meeting on February 25-27, 1962, it was proposed that an astronomer be present during the astronaut's debriefing to note and interpret any observation the astronaut had made. The Ad Hoc Committee for Scientific Tasks for Man- in-Space coordinated and reviewed experiments for the Mercury flights. Because of the space limitations, the lack of a suitable telescope, the lack of a large viewing port, and because of other demands on the astronaut's time, none of the experiments performed were of an astronomical nature. In subsequent meetings, one of the main areas of concern of the Astronomy Subcommittee was the role of man, his limitations, and his training and preparation. Attention was shifted from the Mercury flights to the Gemini-Apollo series in an attempt to have meaningful experiments ready for these flights. A careful set of ground rules was chosen for these experiments. In addition to fulfilling the space, weight and power limi- tations of the space capsule, and being of great value scientifically, the experiments had to be such that their performance was greatly enhanced by the presence of a man and/or some [3] portion of the experiment required reliable recovery. One of the main concerns at this time was that the observing port be of adequate size and have good transmission in the ultraviolet and visible. The February 4-5, 1963, subcommittee meeting was held at Houston at the Manned Spacecraft Center. The facilities were inspected and, in a detailed presentation, D. Slayton of MSC explained the training background and special problems of the astronaut.

 Manned Flight Experiments Working Groups Toward the end of the Mercury program, the Ad Hoc Committee for Scientific Tasks for Man-in-Space was disbanded and a Panel on In-Flight Scientific Experiments (POISE) was formed which was chaired by Drs. Gill and John O'Keefe. This panel was originally established to provide coordination between the Manned Spacecraft Center and in-flight experimenters. This panel reviewed over 100 experiments, 12 of which were then sent to the Manned Space Flight Experiments Board (MSFEB) and the Space Science Steering Committee (SSSC) for approval. Early in 1963 after the initial experiments had been selected for the Gemini flight program, POISE was discontinued. Subsequent manned space experiment review was performed by the regular subcommittees of the SSSC. A new group was formed consisting of flight experimenters, Manned Spacecraft Center person- nel, and NASA Headquarters personnel which is called the In-Flight Experimenters [4] group. Its purpose is to continue the coordination activities of POISE. This group was chaired by Dr. Gill and has been responsible for bringing about some improvements in the experimenters conditions on board Gemini and Apollo. A specific example is that of the Gemini observations port which is now protected during launch to prevent scratches and contamination from obscuring the pane. In order to provide coordination between the various subcommittees of the SSSC and manned flight experiments program, a committee was formed called the Manned Space Science Working Group. This committee was composed of a member of each of the sub- committees and was chaired by Mr. Willis B. Foster, the Director of Manned Flight Experiments in the Office of Space Science and Applications (OSSA). This group met twice, January 30 and March 26, 1964. The meetings were largely informative, i.e., for the purpose of explaining the manned space science programs. The main concern of the members of the group was with experiment opportunities on the various spacecraft and the methods which should be used to publicize these opportunities in the scientific com- munity. The group members as a whole were quite critical of NASA's apparent delay in doing this. Concurrent with the Manned Space Science Working group, separate disciplinary panels were meeting to determine the need and possible [5] experiments which might be performed using an Orbiting Research Laboratory (ORL). The Astronomy Panel met twice on October 26, 1963, and June 24, 1964. Dr. Peter C. Badgley of Manned Flight Experiments of OSSA presided and 18 astronomers and physicists attended who had demonstrated a previous interest in space astronomy. This panel set as its goal an 120-inch diffraction-limited telescope in orbit around the earth. The panel then formulated a gen- eral list of experiments to be performed with such a telescope. The panel noted in its rec- ommendation that a growing group of astronomers felt an urgent need for an immediate study of the detailed problems of manned space astronomy. They then delineated some of the specific problems expected. They felt that solutions to these problems should involve a large part of the astronomical community and that a consensus be obtained, although the panel did not know how to initiate such a program. Another group also met at this time to formulate experiments for the early Apollo missions. This was known as the Ad Hoc Working Group on Apollo Experiments and Training on the Scientific Aspects of the Apollo Program. This group, under the direction of Dr. Charles P. Sonett, had as its prime interest the study of selenography, planetology

EXPLORING THE UNKNOWN 595 and aeronomy. They published one report December 15, 1963. They considered the pos- sibility of the astronaut's doing astronomical experiments but concluded that “the initial Apollo missions should not [6] be burdened by astronomical activities." Apollo and Manned Space Station Studies At the May 23, 1963, Astronomy Subcommittee meeting, the members were asked their views on the scientific value of a manned space station. Most of the members felt that it was not justifiable at that time on a scientific basis, but that this might change once the limitations of unmanned observatories were determined. At the following meeting, August 8-9, 1963, Dr. L. Roberts of the Langley Research Center presented a report to the Astronomy Subcommittee on a feasibility study for a large manned orbiting astronomical telescope. The study had been carried out at Langley. Although the astronomical uses of the telescope generated by the study were felt by the subcommittee to be unrealistic, they felt it was a valuable study because the engineering aspects that were developed. It is necessary to know the engineering design parameters because these determine the constraints which must be placed on a related telescope. At the same meeting a representative from the Manned Spacecraft Center presented their long range plan for a Manned Space Station. At the November 7-8, 1963, Astronomy Subcommittee meeting, several proposals were reviewed for flight on Gemini spacecraft. The proposals [7] that were recommend- ed by the subcommittee were for a general purpose telescope by the University of Arizona; an X-ray astronomy proposal by the American Science and Engineering; and a proposal for the operation of a small fully stabilized telescope by Lowell Observatory. The advan- tages and disadvantages of a lunar-based observatory were compared with those of an orbiting platform at the May 6, 1964, Astronomy Subcommittee meeting. Also, at the same meeting, Dr. Harlan Smith made a report on the activities of the Manned Space Working Group. He described the method of selecting experiments for the Apollo program. This was done by approaching certain scientists directly. Then, at a meeting held at the MSC on June 15, 1964, the potential experimenters were to present their ideas for experiments. On August 11, 1964, a letter was sent out to many astronomers at various institutions, informing them of the opportunity to participate in the design of flight instruments and telescope systems which were larger than those currently scheduled and which would use a man in conjunction with these instruments. Those responding to this letter were to define the research objectives, to estimate the technical requirements to reach those objectives, and to identify engineering problems which would the demand particular attention. Essentially, the only response to this invitation was by Princeton University, with Dr. Lyman Spitzer as the principal investigator. Their proposal was for the design of a [8] diffraction-limited orbital telescope for direct imagery and ultraviolet spectrophotometry. At the time of the May 6-7, 1964, joint subcommittee meeting of the Astronomy Subcommittee and the Solar Physics Subcommittee, the following recommendation was jointly adopted: Both subcommittees resolved that it was their belief “that the vital part of both stellar and solar astronomy lies in the establishment of large astronomical observing equipment in space. This equipment should be a logical outgrowth of the currently planned OAO and AOSO programs and should utilize the best technology available at that time." At the October 28-30, 1964, meeting of the Astronomy Subcommittee, it was decided that the subcommittee would review all proposals which had been submitted for a manned orbiting telescope in answer to a request for proposals originating with Dr. Leonard Roberts of the Langley Research Center. As a result of this invitation, the University of Virginia developed the astronomical objectives and requirements of a large orbiting telescope, the Fecker Division of the American Optical Company studied the optical feasibility of such a telescope and the Boeing Aircraft Company investigated the mission and engineering requirements. At this time considerable debate was occurring about whether the future needs of manned astronomy and science in general could be served [9] by adaptation and modification of the existing Apollo spacecraft system or if an entire new generation of spacecraft would be required. This problem was further complicated by the military requirements of the Department of Defense. In order to answer these questions, several industrial compa- nies were funded to generate lists of manned scientific experiments which could be flown on Apollo. They were aided in this by several government panels. On February 1, 1965, an ad hoc panel was chaired by Dr. Henry Smith. The purpose of this panel, known as the Astronomy and Astrophysics Panel for Experiment Recommendations for the Earth Orbital Apollo Missions, was to review the astronomical experiments which had been proposed for Apollo. Dr. Smith's panel reviewed over two dozen experiments, fifteen of which were found worthy of flight consideration. These experiments were used as a planning basis for a post-lunar Apollo program which was to become known as the Apollo Extension Program (AEP). These experiments were later reviewed in detail by other reviewing groups. The AEP program, later to become known as the Advanced Apollo Program (AAP), will be discussed in greater detail under the sec- tion entitled Flight Experiments. [10] SECTION II - PROGRAM PLANNING Several alternatives were considered as possible manned astronomical programs to follow the Gemini and Apollo Lunar Missions. These alternatives required that a decision be made as to whether the Apollo Hardware could be modified to allow the accomplishment of future scientific requirements or would a new spacecraft have to be developed. This decision was further complicated by the requirement that NASA and the Department of Defense (DOD) might have to share the same vehicle. This choice was simplified when the President of the United States, on August 25, 1965, authorized DOD to develop a Manned Orbiting Laboratory for military use. This laboratory was to have a two-man crew and unmanned launches were to begin in 1968. The Air Force selected Douglas Aircraft Company, Inc., to build the spacecraft, with the General Electric Company being responsible for the experiments. The launch vehicle was to be a Titan 3C booster with a NASA Gemini capsule used for the return to the earth. With this decision, military requirements no longer had to be considered when develop- ing a civilian manned space program. NASA chose to plan their future programs around the use of the modified Apollo spacecraft and this new series of missions was to be known as the Apollo-Extension Program (AEP), which later became the Apollo Applications Program (AAP). Following the AAP, it was assumed [11] that experiments would probably be done from a space sta-

EXPLORING THE UNKNOWN 597 tion orbiting the earth and for planning purposes this space station was named the Manned Orbiting Research Laboratory (MORL). The decision to use Apollo for the advanced manned scientific missions was based on the following reasons: first, the Apollo capsule was able to meet many mission require- ments as a result of the capability which was built into the Apollo system when the Lunar Orbit rendezvous mission was selected as the mode to be used for Lunar exploration; sec- ondly, the Apollo spacecraft would be a fully developed and tested vehicle by the time the AAP began; and third, the Apollo/Saturn system represented a national capability which might be lost if a program of this type were not developed for it. Once the decision had been made to pursue a manned astronomical observatory pro- gram based on the use of the Apollo hardware, the definition of particular missions was possible. In defining these missions the work of the previous panels, committees and work- ing groups was incorporated. Experiments which were previously planned for unmanned flight were reevaluated to see if they could gain by being flown in a manned environment. If the presence of a man would increase the lifetime or improve the reliability or reduce the signal bandwidth requirements, some of these experiments were reconsidered [12] for manned flight assignment. New meetings were held to help advise NASA in the for- mulation and priority assignment of different experiments. Many of these meetings were necessary because of the rapid advances which had been made in several areas of astron- omy because of the use of unmanned vehicles. X-ray and gamma-ray astronomy are exam- ples of such rapidly progressing subdisciplines. In addition, new invitations went out to publicize the new opportunities for experiment. An invitation describing the advanced Apollo missions and the opportunities for experiment was sent out to many potential experimenters March 11, 1966. Studies by the National Academy of Sciences Space Science Board Meeting, Woods Hole, Massachusetts. An important meeting in the NASA planning process was held under the auspices of the Space Sciences Board of the National Academy of Sciences at Woods Hole, Massachusetts, on June 20 to July 16, 1965. A report of this meeting entitled “Space Research, Directions for the Future," defined the scientific objectives which should be achieved and made recommendations on how they could be accomplished. The broad research objectives for astronomy were defined as: "(1) Is the Universe finite or infinite, and if it is finite, what is its size? (2) Is the Universe in a steady state, and if not, how did it begin and how will it end? [13] (3) Do the laws of physics as deduced on the Earth apply without change for all times and overall distances? Alternatively, are there fundamental physical laws or phenomena still undiscovered in terrestrial laboratories, that are observable only on an astronomical scale? (4) Were the chemical elements that form all matter built up out of hydrogen, and if so, how? (5) How are stellar systems, stars, and planets, formed?" Their general conclusions were that: 1) Successful study of the planets will require the presence of scientists, either on the planet's surface or orbiting the planet because of com- munication time delay and/or power bandwidth requirements. 2) Man may be successfully employed in space as an observer; for assembly, placement, repair and operation of scientific instruments; for analysis, collection, storage and retrieval of data. 3) The cost of manned space flight can not be justified on the basis of its “scientific value" alone. The working group visualized four types of programs: 1) The current Gemini and Apollo programs; 2) More advanced laboratories such as the Apollo Applications Program (AAP); and 3) Large, special-purpose space laboratories such as optical, radio, X-ray or gamma-ray observatories. Both the optical and solar astronomy panels made recommen- dations that the AAP be utilized as an interim program to gain [14] experience with tele- scopes in the 60- to 80-inch category with a goal of a manned orbiting telescope (MOT) with a 120-inch diameter mirror and usable in the 500 A to 1 mm spectral region. Space Science Board - Large Space Telescope Panel. A large national facility was recommended strongly by the Woods Hole Summer Study and other panels and com- mittees. Although such a facility has been given various titles and it may be lunar rather than orbital, NASA has come to call it MOT (for manned orbiting telescope). As recommended at the Woods Hole meeting, a panel under the chairmanship -of Dr. Lyman Spitzer, Jr., of Princeton University has continued to hold meetings to discuss the problems involved in developing a large space telescope (April 29-30, 1966, and July 17-19, 1966). In their meetings they have considered the scientific program, tech- nical problems and managerial problems. The last meeting mentioned was devoted to developing the scientific objectives in detail. The scientific recommendations of the Woods Hole meeting have been used as guidelines. The committee has accepted the recommendations of NASA as regards the largest diameter mirror which can be placed in orbit with the present generation of launch vehicles. They believe it is rea- sonable to assume that such a mirror (120 inches in diameter) may be made diffrac- tion-limited. If this is not possible, they would prefer to sacrifice the diffraction limitation to total aperture. *** ***** [22] NASA Headquarters OMSF. The Office of Manned Space Flight supported a major study by the International Business Machines Corporation entitled, “ORL Experiment Program,” under Contract NRSw-1215. The ORL (Orbiting Research Laboratory) con- cept is a general one which included many disciplines. This study had as its very com- mendable goal the determination of experiments to be performed by man in space. This goal was not to be accomplished from the “bottom up" by selecting a list of exper- iments compiled from submissions by interested experimenters but rather experiments would be chosen on the basis of their ability to answer fundamental and important ques- tions in a particular discipline. IBM pointed out the following shortcomings in the “bot- tom up" approach: "a. It results in a collection of individual tests, rather than in a cohesive program; the interrelationships of the individual experiments and the extent of their overlap are obscured. b. It lacks a rationale to determine whether the most important experiments have been identified and are being pursued.

EXPLORING THE UNKNOWN 599 c. Few of the suggested experiments are explicitly tied to requirements or ultimate benefits; as a consequence, the resulting [23] programs frequently fail to demon- strate the value of the space station vis-a-vis its cost." Under the Astronomy/Astrophysics discipline IBM defined four main objectives, many subobjectives and 132 knowledge requirements. This list of experiments has been used as a guide on occasion for various studies, although it is incomplete and sometimes trivial. North American Aviation, Inc.: Under Contract NAS 2-1047, North American Aviation did a study of "The Lunar Exploration System for Apollo" (LESA). The purpose of this investigation was to develop a description of scientific operations that can be car- ried out on the moon with LESA. The LESA system includes a family of prefabricated modules that can be assembled on or below the lunar surface in a variety of arrays. Recommended scientific investigations were obtained from each of nine -panels. Three of the panels which considered astronomical experiments were: Optical Astronomy, Radio Astronomy and Wave Propagation, and Radiation which treated Ultraviolet, X- and Gamma-Ray, and Neutrino Astronomy. The various experiments were divided up to be performed on early and on late missions. In case of Optical Astronomy the early mission would use a 40-inch lunar--based telescope for multihour exposures. The later missions would employ a 120 inch instrument. Langley Research Center. Langley Research Center, an Office of Advanced Research and Technology (OART) center took an early interest [24] in the problems associated with manned astronomical experiments in space. Most of their studies were done by con- tract under Associate Director, C. J. Donlan. This work was carried out by P. Hill who head- ed the Manned Orbital Research Laboratory (MORL) Steering Committee, Dr. L. Roberts who was in charge of the Manned Orbital Telescope (MOT) Steering Committee, and W. Gardner who headed the MORL Study Group. The Langley people came to the conclusion (based on their early studies) that a tele- scope employing a 120-inch mirror which had the structural integrity to be diffraction lim- ited was the largest telescope which could be launched on the Saturn series of vehicles. This determination has been generally accepted in all other studies. Douglas Aircraft Co.: One of the earliest studies was that by Douglas Aircraft Co. with International Business Machines (IBM) as a subcontractor. This study was initiated by the MORL Study Group and was completed January 1966. Its purpose was to define and optimize typical missions using MORL. This study was accomplished in three phas- es: Phase I (June-September 1963) System Comparison and Selection Study of a Manned Orbital Research Laboratory; Phase I A[sic; should be IIA] (December 1963 - November 1964) Optimization of the MORL System Concept and Phase II B (December 1964 - January 1966) Development of the MORL System Utilization Potential. Phase I demonstrated the feasibility of launching, operating, and maintaining a manned research laboratory. Phase II A defined the MORL concept [25] to include a (1) 260 inch dia. laboratory launched by the Saturn IB in a 200 nautical mile orbit inclined at 28.72º to the equator; (2) a Saturn IB launched Apollo logistics spacecraft and; (3) supporting ground systems. Phase II B examined experiments from NASA, and Department of Defense (DOD) sources redefined them and collated them, and commonality was searched for. This was done to determine the utilization potential of the MORL system concept.

 University of Virginia: The MOT Steering Committee supported an investigation by Dr. Laurence W. Fredrick of the University of Virginia entitled, “Applications in Astronomy Suitable for Study by Means of Manned Orbiting Observatories and Related Instrumentation and Operational Requirements." The resulting report considered the following areas appropriate for research with a MOT: Stellar Mass Determination: The ability of an orbiting telescope to determine mass depends on (a) the theoretical resolu- tion limit and (b) the accuracy of guiding during exposure. With a guiding accuracy of only 0.3 seconds of arc, masses of at least 30 new binaries may be determined. Cosmological Tests: The concept of uniformity in general relativity may be tested by an intercomparison between brightness distances and size distances. High Resolution Photography and Spectroscopy: Photography with the resolution possible in space is important to all fields of astronomy. Increased spatial resolution will allow increased spec- tral resolution which is needed in all spectral regions. Infrared Observatories: Because of the longer observing times available and low sky temperatures, infrared observations from a MOT should be two orders of magnitude better than observations from a comparable telescope on earth even in the [26] windows and of course infinitely better in the opaque portions of the atmosphere. Measurement of stellar diameters: Interferometric and image orthicontechniques on a MOT should allow stellar diameters to be measured down to 0.0005 seconds of arc. The Study of Regions of Polarization: Techniques which have been used to study polarization in the visual spectral region could be extended to other spec- tral regions. The Search for Very Faint Stellar Companions: An apodizing device could be constructed for a MOT which would not increase the definition of a star but would enable close faint objects to be detected. Integrated Studies of Comets: The large aperture of the MOT would allow studies of comets to be made as they become fainter after leaving the sun and long intergarion times would not be needed. Also comets could be observed in all spectral regions and their behavior monitored. American Optical Company: In 1964 the MOT Steering Committee funded the J. W. Fecker Division of the American Optical Company at Pittsburgh, Pennsylvania, to do a "Feasibility Study of a 120-inch Orbiting Astronomical Telescope” report AE-1148. They looked at the optical problems involved. They did ray tracing and developed some optical configurations. They chose a cassegrain configuration with an f/2 parabola for the pri- mary mirror which could be used with different optical components to give a range of focal ratios from f/2 to f/100. Although their design was not optimized they felt that they had demonstrated feasibility. One of the most severe problems they encountered was maintaining the alignment of the secondary mirror, but they felt this could be accom- plished by the use of an active system [27] with a laser and interferometric techniques. Boeing Aircraft Company: The University of Virginia and American Optical Company studies served as a starting point for a rather thorough study by the Boeing Company of Seattle entitled "A System Study of a Manned Orbital Telescope" D2-84042-1, October 1965 and a continuation, “Synchronous Orbit Study” D2-84042-2, April 1966. General Electric was retained as attitude stability and control subcontractor and Drs. Zdenek Kopal of the University of Manchester, and James G. Baker of Harvard served as consultants. This report did much to establish the 120 inch telescope as the largest size which could be launched. The limiting stellar magnitudes presented may be too bright by as much as five magnitudes.

EXPLORING THE UNKNOWN 601 The principal results of the Boeing Study were: Astronomy and Optics-The astro- nomical objectives of The Virginia Study were accepted almost in total. A Ritchey-Chretein modification of the pure Cassegrainian System was selected with an f/4 primary and two secondary mirrors which permit operation of the telescope at f/15 and f/30. Necessary instrumentation was designed conceptually. Operations Analysis—The role and contribu- tions of man were carefully delineated. The study of the operation of the MOT was nar- rowed down to three basic modes which used the MOT in conjunction with the MORL as defined by Douglas in their study. The preferred modes were a detached mode capable of docking with the MORL but employing a shuttle for normal operations and a soft [28] gimballed mode. Configuration■ Various configurations were examined. Launch and orbital configurations for the two select- ed modes of operation were developed. Scientific instrumentation and cabin arrangement for the MOT were also defined. Structures—The primary structural design was based on the boost condition. Special attention was given to the primary mirror stresses during the boost and docking, the dynamics of the soft gimbal made, thermal distortions of the primary mir- ror during operation and meteoroids and radiation. Attitude Stability and Control-The observational requirements were used as the basis from which to synthesize an attitude con- trol system. The study showed that it would be feasible to stabilize the telescope to within 0.01 seconds of arc. A pointing error for the soft gimbal concept of about 0.003 seconds greater than for the detached mode was indicated. Thermal Analysis-Computer studies were per- formed to determine the thermal gradients in the primary and secondary mirrors and the telescope structure. The use of an earthshade and doors that closed when the optics were pointed towards the earth greatly aleviated [sic] many thermal problems. The general conclusions were that the MOT was a feasible system and that the soft gimbal mode would be preferable. A synchronous orbit is feasible and it would allow longer observation times with reduced thermal problems. In addition to the above, Boeing outlined several special problems including optics manufacture, film handling an [sic] attitude stability control. Marshall Space Flight Center. The Marshall Space Flight Center (MSFC) has sup- ported studies to develop programs to follow the early Apollo lunar missions and which would utilize the talent and hardware which were developed for Apollo. ******** [43] The Manned Orbiting Telescope (MOT) The term “manned orbiting telescope" has been used rather ambiguously in NASA. It originally referred to any program which employed a telescope and utilized a man to set it in operation and to maintain and operate it. It was usually assumed that this telescope was in an earth orbit but telescopes operating from the moon have also been considered under this title. More recently the designation MOT has been reserved for telescopes not connected with AAP. Earth orbiting telescopes connected with AAP are now called ATM and MOT is reserved for another generation of missions. In recent usage, MOT also refers more specifically to a major national astronomical facility in space. In addition to the MOT studies referred to in Section II, NASA Headquarters has made two additional studies. The first was “The National Astronomical Space

602 NASA AND PLANETARY EXPLORATION Observatories Working Group Report," August 16, 1966. This report was generated for the Planning Coordination Steering Committee of NASA Headquarters. This document describes the major astronomical problems that exist and then describes how a 120--inch diffraction-limited telescope would help find the answers to these problems. It has been thought by many that, to be most effective, at least one and perhaps several astronomers will have to spend their full time with MOT. In order to support these astronomers some sort of a space station will be required. A study has been made of space stations and [44] their associated problems which is entitled “The Needs and Requirements for a Manned Space Station," September 28, 1966. This report was prepared by the Space Station Requirements Steering Committee, and dis- cusses in depth the justifications for a space station; an MOT is one [sic] the more important justifications. Document III-14 Document title: NASA Management Instruction 1156.16—“NASA Astronomy Missions Advisory Board," September 25, 1967. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Document III-15 Document title: NASA, “A Long-range Program in Space Astronomy, Position Paper of the Astronomy Missions Board,” NASA, edited by Robert O. Doyle, Harvard College Observatory, July 1969. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. While it did not immediately embrace the idea of establishing an external organization to manage the scientific operations of a space-based astronomical facility, NASA's head of space science, Homer Newell, in reaction to the Ramsey report, suggested creating a standing group of academic astronomers to advise NASA on astronomy program objectives and strategies. The new group, the Astronomy Missions Board (AMB), was chartered in 1967 to address astronomy needs, just as the Lunar and Planetary Missions Board supported the solar system exploration program. In July 1969, the AMB issued a long-range program in space astronomy, outlining the most pressing prob- lems and the types of observations and instruments necessary to solve these problems. After more than two years of meeting regularly, after preparing this report the AMB ceased functioning because of board members' frustration that NASA never acted on its recommendations due to lack of funds to conduct suggested programs.

[1] EXPLORING THE UNKNOWN Document III-14 Management Instruction 603 NMI 1156.16 September 25, 1967 Effective date SUBJECT: NASA ASTRONOMY MISSIONS ADVISORY BOARD 1. PURPOSE This Instruction establishes the NASA Astronomy Missions Advisory Board and sets forth its functions and scope of interests. 2. AUTHORITY a. Section 203 (b) (7) of the National Aeronautics and Space Act of 1958 (42 U.S.C. 2473 (b) (7)). b. Executive Order 11007 (February 26, 1962). C. NMI 1150.2. 3. ESTABLISHMENT a. (1) The NASA Astronomy Missions Advisory Board (hereafter referred to as the "Board") is hereby established to assist NASA in the planning and conduct of all NASA missions to create and operate astronomical telescopes in space. (2) The long-range continuing objectives of astronomy are to learn by remote observation the structure and behavior, the origin, growth, and demise of all types of celestial bodies, ranging from the smallest (meteorites, comets, and planets) to the largest, including stars, star systems, the matter in space, and the entire cosmos. The telescopes utilized by space astronomy work over the whole range of the electromagnetic spectrum, from gamma rays, through X-rays, the ultraviolet, visible light, infrared light, and radio frequency radiation. (3) Excluded from the Board's area of responsibility are missions to study the moon and planets from a close vantage point, or in earth orbit for study of the earth. b. Pursuant to Executive Order 11007 and paragraph 6 of NMI 1150.2 it has been determined that the formation and use of the Board is in the public interest. The Board is not an “industry advisory committee” within the meaning of para- graph 5b of NMI 1150.2.

 [2]4. FUNCTIONS The Board will serve in an advisory capacity only. Organizationally, the Board will be responsible to the Associate Administrator. Determination as to any action to be taken which is based in whole or in part on proposals or recommendations of such Board shall be made solely by appropriate full-time salaried officials or employees of NASA. The scope of the Board's activities include, but are not limited to: a. b. C. d. e. f. The development and review of the scientific objectives and general strategy for space astronomy and associated ground-based astronomy. The review of support of ground-based astronomy and observations from sounding rockets, balloons and aircraft as well as satellites. The formulation of guidelines and specific recommendations for the design of space astronomy missions, and for the various telescopes and auxiliary equip- ment to be developed and used on these missions. The continuing review of the way these missions are meeting the needs of cur- rent scientific objectives and strategy. The continuing examination of policies relating to the operation of these tele- scopes in the space observatory once they have been made operational and are available for observations by the scientific community. The development and improvement of mechanisms by which the NASA space astronomy program can get the best assistance from, and give the most help to, the entire community of astronomers and space physicists. 5. MEMBERSHIP a. b. The Board shall be composed of about 12 scientists and engineers, all of whom are broadly experienced in the technology and scientific discipline of astrono- my. To be proportionately representative of the astronomical community at large, the membership majority will normally not be made up of full-time NASA employees. The Board Chairman will be designated from among the non-NASA members of the Board. The Board will also have an Executive Director who shall be a full-time salaried employee of NASA, but who will not be a member of the Board. The Board and its Chairman will be appointed by the Administrator, and will serve at his pleasure. The Executive Director will be appointed by the Associate Administrator. The Administrator will consult with the Board on any appoint- ments to the Board. 6. BOARD RELATIONSHIPS a. The Board will have a close working relationship, through the Associate Administrator, with senior NASA officials and organizational elements involved. Requests for advice and recommendations will be made to the Board through the Associate Administrator. Similarly, the Board will request studies or other

EXPLORING THE UNKNOWN 605 assistance required from other groups in or out of NASA through the Associate Administrator. Document III-15 [cover sheet] NASA SP-213 A LONG-RANGE PROGRAM IN SPACE ASTRONOMY Position Paper of the Astronomy Missions Board July 1969 Edited by ROBERT O. DOYLE Harvard College Observatory Cambridge, Mass. [iii] PREFACE The Astronomy Missions Board was established by the National Aeronautics and Space Administration by charter in September 1967 to assist in an advisory capacity in the planning and conduct of all NASA missions to create and operate astronomical experi- ments in space. The scope of the Board's activities includes development and review of the scientific objectives and general strategy for space astronomy and associated ground-based astronomy; the formulation of guidelines and specific recommendations for the design of space astronomy missions, and for the various experiments and auxiliary equipment to be developed and used on these missions; the continuing examination of policies relating to the operation of these space observatories once they have been made operational and are available for observations by the scientific community. The work of the Board encom- passes the many aspects of space astronomy including direct observations of electromag- netic radiation from astronomical sources, cosmic-ray particles and the supporting research that is necessary, but its scope does not include the study of the Moon and plan- ets from close vantage point or study of the Earth.

 The Astronomy Missions Board is presently composed of 18 members of the scien- tific community with a wide diversity of interests and experience. They are drawn large- ly from universi-ties, but include members from national laboratories (see appendix for a list of members of the Board and its panels) [appendix not included]. The Board's activities are supported and supplemented by seven panels and two ad hoc working groups to whom specific areas of responsibility are assigned. The panel compositions are similar to that of the Board itself and involve an additional 31 scientists. This wide membership provides a broad representation of current thought in space astronomy both directly through its membership and from the wider astronomical community by means of letters and discussions. The activity of the Board has been intensive. With few exceptions, it has met month- ly for 2 days at locations appropriate to its current activities. In addition to extensive delib- erations and [iv] discussions, the meetings have included reports and resumes from NASA personnel about matters such as the current status of projects then underway, present NASA plans for the future, technical reports on areas of special relevance, and bud- getary aspects of current and planned programs. The panels have met several times dur- ing the past year and have taken the opportunities for obtaining firsthand information about the activities in space astronomy at various NASA centers relevant to their particu- lar fields of interest. Again, briefings as to technical capabilities and current planning were obtained and the panels prepared detailed programs and recommendations for activities in their areas. An important continuing activity of the Board is the presentation of specific recom- mendations to the Associate Administrator of NASA. Many of these recommendations have been ad hoc answers to questions raised by NASA, while others have been of a more general nature and have, in most cases, been incorporated into the body of this report. Many of these ad hoc recommendations were for the purpose of assisting NASA to opti- mize a low-level program, and should not be construed as approval of such a program by the Board or the scientific community. The Board has created a long-range national program for space astronomy-including discussions of the major problems of astronomy and astrophysics, an observing program describing the next important measurements from space, and examples of the instru- ments, spacecraft, and missions needed to make those measurements. Specific mission descriptions are not intended as concrete definitions of future missions, but as part of an exemplary program which is used to establish the best current balance between the sub- disciplines. The plan contains sufficient mission priorities and interdependences on which to base AMB advice to NASA at various foreseeable levels of effort, and should enable NASA management to assess the impact on scientific progress of the various future options available to them. The purpose of this position paper is to describe the long-range plan as it appears in July 1969. Past experience has shown that astronomy is a field full of surprises and the unex- pected, and it would be extremely shortsighted to expect this report to remain up to date for very long. This report is not intended to be a static document. It is, rather, a working paper to be updated and altered continuously by the Board as technical capabilities change and scientific opportunities and priorities evolve. Nevertheless, it seems appropri- ate to publish [v] this version of the position paper, just as it was submitted to NASA as

EXPLORING THE UNKNOWN 607 part of the fiscal year 1971 budget planning cycle, in order to acquaint a wide communi- ty of astronomers, astrophysicists, physicists, and other interested scientists with the work- ings of the Astronomy Missions Board, as well as with the national space astronomy program. NASA and the Astronomy Missions Board hope in this way to continue to improve the mechanisms by which the NASA space astronomy program can get the best assistance from, and give the most help to, the entire community of astronomers and space physicists. From time to time, as the extent of the revisions makes a major part of this work obsolete, the Board will again publish an updated position paper. The detailed reports on the subdisciplines of space astronomy, authored by the pan- els and endorsed in substance by the Board, will be found in Part II[not included]. Part III describes how the panels' programs were evaluated, and how parts of them were com- bined into long-range plans at two levels of effort-a minimum balanced program and an optimum program-both of which do not attempt simply to do everything suggested by the subdisciplines, but rather emphasize research on those problems judged astrophysically most important by the greatest consensus of the Board. A summary of the position paper and key features of the long-range plan will be found in Part VII [not included]. ******** [223] III AMB LONG-RANGE PLAN FOR SPACE ASTRONOMY [227] THE TWO AMB LONG-RANGE PLANS Before presenting the final mission schedules, we should briefly define each of the long-range plans-describing the characteristics that the AMB hoped to impart to these composite programs. The Minimum Balanced Program The definition of a minimum program, especially the concept of a sharp break below which progress becomes substantially more difficult if not impossible, is often an exercise fraught with the possibility of misunderstanding. We therefore emphasize the significance of the AMB minimum balanced program as that level below which one or more of the sub- disciplines of astronomy must be dropped to maintain the others above their minimum thresholds of efficient and scientifically profitable operation. Such a negative step would then seriously undermine a central assumption of the Board's planning; namely, that the agreement between the subdisciplines on the most important astrophysical problems requires an orchestration of the multiwavelength observing programs. This assumption is that for many problems a few relatively unsophis- ticated, and sometimes less expensive, measurements in different wavelength regions might lead to a deeper [228] understanding of the physics of a process—than a most beautiful detailed picture achieved at great cost at a single wavelength. This is not to say that in some cases the narrow, highly specialized approach might not produce the essen- tial, even indispensable, key. It is simply a judgment of the Board about the requirements for greatest progress in most problems before us at the present time. We should also note in passing that the Board found it was often these problems requiring a multiwavelength, multidisciplinary approach, which are the problems attracting so many physicists and sci- entists from other disciplines to come to work in modern astrophysics. A timely example of the lengths to which scientists will go to achieve the completeness of the multiwavelength approach, and an illustration of the uses to which the future capa- bility in space astronomy will be put, is the current standby alert trying to catch the bril- liant flash of a flare in the X-ray star, Sco XR-1. Starting in May, astronomers at Cerro Tololo Observatory in Chile have been continuously measuring the visible radiation, watching for the onset of a flare. At the first sign of activity, they will radio other astronomers at Caltech where the 200-inch Mount Palomar telescope will make infrared observations, in Hawaii where a rocket will be launched to record the X-ray spectrum, and at Goddard Space Flight Center where University of Wisconsin experimenters will turn the Orbiting Astronomical Observatory's ultraviolet telescopes toward the X-ray star. Since the Australians recently discovered Sco XR-1 to be a strong variable at radio wavelengths, a large steerable radio telescope may also be used to complete the wavelength coverage. The great hope is to achieve several measurements whose combined value in terms of sci- entific understanding might greatly exceed the combined cost relative to that of any one of the measurements standing alone. The Optimum Program Although the concept of an optimum program is usually less controversial than a min- imum program, the Board wants to take pains to stress that this is not simply a program in which the subdisciplines all are encouraged to do their maximum unconstrained pro- grams. First, it was composed from a set of subdiscipline maximum programs where the principal constraint, or upper limit, was the projected availability of excellent people-sci- entists and supporting teams of specialists-to carry out the recommended missions. Second, the level of the resulting optimum Board program was about 20 percent below the sum of the maximum subdiscipline [229] Finally, the Board's priority assignments again raised and lowered the levels of the individual programs to accomplish a unity and balance with prospects for greatly multiplied combined benefits. FLIGHT SCHEDULES On the following pages we present the schedules of space astronomy missions which implicitly contain the best judgment of the Astronomy Missions Board concerning the present optimum balance of effort between the various subdiscipline programs, as those programs were described in part II. These schedules cannot be adequately interpreted without recourse to the subdiscipline reports where the observational programs and mission objectives are developed. We present here a brief description of the structure of the schedules and a glos- sary of terms and abbreviations which will assist the reader in referring back to a particu- lar subdiscipline report for further information. The minimum balanced program flight schedules are shown in table 1 (Astronomy Missions) and table 2 (Space Physics and Interplanetary Missions). The optimum programs are shown in tables 3 and 4. The gen- eral plan of the Astronomy Tables 1 and 3 shows increasingly expensive types of missions arranged vertically in successive blocks. Each block contains spacecraft which are approx- imately a factor of 2 more expensive than the preceding block. Within each block one row

EXPLORING THE UNKNOWN 609 is given to each of the subdisciplines, with one exception (X-X and g■ray, O■Optical UV and IR, R-Radio, S-Solar, P-Planetary). [230] Darkne TABLE L—Minimum Balanced Program-Astronomy _ ............. - barb wyalchi platform-$131/vzul 141414141414141 " ± ** --- - ur ■■■■ ■ 080-7 65-06-1 10-mu F +Part L ■ IÓ-2 DIO-q ▲ LONG-BANG. PROGRAM IN SPACE ASTRONOMY TABLE 2. „Minimus Program for Fields and Portiels Astronomy (Astronomy Portion) Beach ( Lat Me (Explo/poletis pel). Over Bankma", (la pecin t■ "a pinnak (1) La valythe phone. (3) of adliyija plan■. (a) Marko Mar (we Ying) Jaz Pro (4) Tamara Fal (3) Q/11. miez prob [er past■ to 11 AU…. Large bed experienta (or Apa Applications wit plangens Y 1)M Rockle T IL N.O | 7.9|21|20| VW LY ■ G.D H " " M 10 14 A- ▲ 2,0 b -- " Gaze 5.| DIE -------TT. H (I) DT -

610 NASA AND PLANETARY EXPLORATION ******** [234] X-Ray and y-Ray Missions Balloons.—Continued pointed flights—y-ray continuum studies■reach 103 CM2 sec1 level at 105 eV for selected X-ray discrete sources. Rockets. Broad participation-quick turnaround. Explorers.-SAS-A: sky survey sensitivity 104 Sco X-1; 1-8 keV, 0.5° resolution, broad- band spectral resolution; SAS-B: high-energy y-ray survey 106 $CM^2$ $sec^1$; SAS-C and beyond: extend energy response 200 eV to 1 MeV, larger spark chamber devices, improve pointing to study sources, time variations. OSO. Continued use of wheel section for surveys, monitoring. OAO or equivalent.—First stellar X-ray imaging telescope positions to -1 arcsec, 2/2 to ~ 0.01 for sources to 104 Sco X-1. Instrumentation state of art. OWSE.■High-sensitivity X-ray and nuclear - g-ray surveys, nuclear lines and continuum studies; large Cerenkov telescopes, 108 $CM^2$ $sec^1$ above 500 MeV, crude energy resolution. Heavy Explorers.-A: high-sensitivity X-ray survey 10° Sco X-1, 0.1° resolution, nuclear y-ray survey chamber 107 $cm^2$ $sec^1$, Cerenkov telescope; B: extend sensitivity, broad energy resolution, increase angular resolution-study continuum y-rays from known extra- galactic X-ray sources. OXO.—Stellar X-ray imaging telescopes, design goal -1-m aperture, interchangeable instruments at focus to accommodate image detectors, polarimeters, spectrometers. 5-10-m X-ray telescope.—A permanent National Space Observatory. Optical Highlights Structure and processes in the outer atmospheres of stars—especially extremes such as very hot, very cold, and very unstable objects-hold clues to the history and fate of stars. Stellar spectrophotometry in the UV can give information on such stellar chromosphere and coronas, adding to our knowledge of similar solar activity which controls solar-inter- planetary-terrestrial relationships. Absorption line measurements in the UV are three orders of magnitude [235] more sensitive than visible lines in detecting the interstellar gas, helping to determine chemical composition, physical state, and energy balance of the interstellar medium. Continuous spectrophotometric measures of planetary atmospheres, comets, and the interplanetary medium will help us to understand the origin and present nature of our planetary system. Spectrophotometric UV and IR observations of gas ejection from galactic nuclei, together with high-resolution images of these objects, will help unravel these explosive events whose extreme dynamic conditions play a fascinating role in the evolution of stellar systems and which may lead to new knowledge of fundamental physics. Optical Missions Airplanes and balloons.-IR telescopes, from 36 inches in minimum program to a pos- sible 120 inches in maximum; balance flights between large platforms such as Convair 990 and smaller single experiment flights such as Lear Jets. High-resolution visible telescopes (Stratoscope).

 Rockets. UV spectrographs, 1-X resolution, for studies of stellar atmospheres and interstellar absorption lines. Possible standby for a bright comet. Far IR broad-band scan of sky for emission from interstellar dust grains and sources with peak intensities at wavelengths greater than 20 m. SAS.■Broadband UV photometer and polarimeter, selective extinction and polariza- tion by grains, variable stars and galaxies, solar-system objects. UV sky survey.—Interstellar gas emission at several wavelengths. IR telescope. Probably refrigerated-10-100 m for the study of planets, stars, gas, grains. OAO-B (GSFC).—UV scanning spectrometer 2-X resolution, stars and nebulae; OAO-C (Princeton) UV scanning spectrometer 0.1- and 0.4-Å widths, interstellar absorption in stars to 6th magnitude, stellar spectra; OAO-D (national facility): UV scanning spectrom- eter with offset guidance, 0.3-0.5 Å width, spectra to 8th magnitude, 40-Å resolution to 13th magnitude; OAO-E (National): wideband UV spectrophotometer and polarimeter, offset guidance, galaxies, variable stars, interstellar grains; OAO-F (National) UV echelle spec- trometer with integrating TV tube, width 0.1 Å to 9th magnitude, 100 Å to 18th magnitude; OAO-G (National): IR interferometric spectrometer plus broadband IR photometer, light-weight cryogenics system, later flights include improved versions of E, F, and G. Astra.■A: UV echelle spectrometer, high-resolution imagery with filters to magnitude 26 in visible; B: more flexible instrumentation; C: include IR capability. Large space telescope.-Aperture 120 inches or more with resolution corresponding to 120 inches, indefinite life. See LST report of the National Academy of Sciences. Infrared Highlights Infrared detector technology and infrared astronomical discovery are together under- going revolutionary developments in which there are increasing advantages in making observations outside the atmosphere. Infrared space observations will permit-■ (1) Observations of extended faint objects. (2) Observation in the five octaves of spectrum from 25-700 m. [237] (3) Broadband observations of extremely faint objects with detectors limited only by celestial radiation. Fields of study already known to be able to profit from these capabilities are■ (1) The stellar and dust structure of our galaxy. (2) High-energy processes that occur in some galactic nuclei and quasars. (3) The role of dust envelopes in the evolution of stars. (4) The role of dust envelopes in the formation of, planetary systems around young stars. (5) The thermal mission and heat balance of planets and the Moon. (6) Infrared background radiation. High-temperature phenomena at remote epochs will have their radiation shifted into the infrared. Thus these studies have poten- tial cosmological significance. Infrared Missions Because of the rapid development possible in detector technology, and the high rate of discovery of new classes of astronomical infrared phenomena from the ground, a major effort must be made in these areas to insure that full possible benefit is obtained from the space observations.

 Significant developments are expected to occur from the use of small high-altitude aircraft, small balloon-borne equipment, and some rocket flights. Major installations appropriate for the next few years include a 36-inch telescope to be used in a stratospheric airplane primarily for point source observations, and a Small Astronomy Satellite to be used for studies of extended objects and for surveys for new objects. Eventually, technological advances and astronomical discoveries may slow down, and it will be necessary to use larger platforms such as an OAO or a Large Space Telescope. Should detector improvement be difficult, this phase would come earlier. Radio Highlights Measure the flux densities of 50 to 100 extragalactic and galactic sources at a number of frequencies around 1 MHz. Map the cosmic background noise level of the full sky at a number of frequencies from 0.5 MHz to 10 MHz. Measure dynamic radio astronomical phenomena and, in particular, record variations of radio emission from the Sun, Jupiter, and other variable radio sources. Measure the brightness distribution across a few individual radio sources which are occulted by the Moon. Obtain data on the statistical parameters of cosmic background noise fluctuation at a few frequencies near 1 MHz. Study variable interplanetary absorption and interplanetary scintillation effects. Solar-system observations will concentrate on understanding physical processes in the solar corona and in the magnetospheres of the planets, especially Jupiter and the Earth. The region in the corona from 1 to 50 solar radii is particularly difficult to reach by opti- cal observations or space probes. Radio Missions Rockets. High apogee (1000 km) experiments; e.g., absolute calibration, 1-5, 5-10 MHz, 100-150 lb. [237] Explorers.—RAE-C ionospheric focusing and magnetospheric noise; RAE D&E: two or more element interferometer-supersynthesis test, location experiments; RAE-F: cosmic radio noise background; RAE-G: solar-system radio monitor. Orbiting radio observatory.-Ten-km filled-aperture antenna, circular polar synchronous orbit-2000-4000 lb. Solar Highlights Improved angular resolution XUV spectra and spectroheliograms may lead to under- standing the mechanism of nonthermal energy production-plasma and magnetic-field interactions; steep density, temperature gradients; shock and magnetohydrodynamic waves; particle transmission and ejection (perhaps the cosmic accelerator); a flow of ener- gy that controls the state of interplanetary space and planetary ionospheres. Absolute photometry of XUV resonance lines of atoms and ions will lead to improved abundance determinations and perhaps settle the question of different abundances at dif- ferent levels in the solar atmosphere. Absolute photometry of the UV continuum will provide direct observation of the tem- perature inversion.

EXPLORING THE UNKNOWN 613 White-light coronagraphs may reveal outward-moving disturbances from flares and other active regions. Visible spectrum observations with very high angular resolution exceeding that possi- ble from below the atmosphere will reveal details of sunspots, flares, prominences, plages, spicules, and the fine network structure. Solar Missions OSO-1: K coronagraph; OSO-J: spectrograph-absolute photometry 300-3000 Å; OSO- L: spectrograph absolute photometry _ < 30 Å; OSO-M: scanning spectroheliograph _ < 300 Å; OSO-N: K coronagraph; OSO-O: scanning spectroheliograph 300-1300 Å; OSO-P: spectrograph line profiles 300-1600 Å; OSO-Q: spectrograph line profiles _ < 300 Å. 5-Arcsec Spacecraft-ATM-A: [238] 1. Scanning spectrometer and spectroheliometer (300-1300 Å). 2. Slitless spectroheliograph, photographic (300-650 Å). 3. Spectrograph, photographic, high X/AX (900-4000 Å). 4. Small-field, large-scale X-ray telescope, and slitless spectroheliograph, photo- graphic (2-60 Å). 5. Large-field X-ray telescope with filters, photographic (2-60 Å). 6. White-light coronagraph, photographic. 5" Spacecraft No. 2: 1. High resolution (__ ~ 0.2") internally pointed telescope, with filters and spec- trograph (1100-30 000 A). 2. Spectrometer for line profiles and spectrum mapping (300-1000 Å). (This is probably a full load.) 5" Spacecraft No. 3: 1, 2. Spectrometers for X-ray spectrum mapping and absolute photometry (2-300 Å). (Probably at least two instruments.) 3, 4. X-ray line profile spectrometers to measure at least the strongest lines (2-300 Å). 5. X-ray imaging instrument (pinhole? Fourier shadowgraph? something else?) (A < 3 Å). Planetary Highlights Small pointed satellites will allow spatial scans of the planets in different spectral regions, which will allow us to deduce the vertical structure of hazy atmospheres (e.g., Venus, Jupiter). Ultraviolet photometry, as well as infrared observations from high-altitude aircraft, will provide critical knowledge of the planetary albedos, necessary to an understanding of the planetary heat budgets. A cloud model is fundamental to interpretation of spectroscopic measurements, which in turn can yield compositions, temperatures, and pressures. Measurements of the planetary hydrogen corona in Lyman-a radiation with high angular resolution (< 1 arcsec) can yield the escape temperature, an essential quantity to studies of evolution of the atmosphere and ionospheric structure. Essential features of a planet's meteorology could be obtained by long-period moni- toring of the atmospheric fine structure with large-aperture instruments in Earth orbit.

 Planetary Missions Rockets.■Survey spectrophotometry at several-Å resolution, 1800-3300 Å. Photometry in far-UV resonance lines, especially Lyman-a (1215 Å). Possibly high-resolution scans of narrow spectral regions of special interest. Explorers.-Extension of sounding rocket objectives but to fainter objects and improved spectral resolution, and with the important addition of spatial resolution over disk. OA O-A2 (WE P).-Broadband photometry, Lyman-a photometry; OAO-B: spec- trophotometry with 10 Å resolution; OAO-C: resolution of 0.1 and 0.4 Å over narrow spec- tral regions of special interest, possibly with spatial scans. Particles and Fields Highlights Observations within the solar system of magnetic fields and particles with energies from 0.5 keV to many GeV yield information on such diverse astrophysical problems as the 3° blackbody radiation, supernovae, the interstellar medium, the dynamical behavior of the galactic disk, nucleosynthesis and the origin of the elements, and stellar abundances— information not available through any other kind of observations or experiments. Cosmic-ray particle studies are related to radio, infrared, ultraviolet, X-ray, and g-ray astronomy measurements across the spectrum from the microwave background to mega- volt photons to form an overall picture which would be inaccessible from optical and radio studies alone. Through couplings between high- and low-energy processes such as the inverse Compton effect, all of the data related to a given object are related to each other and eventually all inputs are needed for a full understanding of the environment. High-energy astrophysics not only adds new windows to the cosmic electromagnetic spectrum by providing X-ray, g-ray, and particle and field astronomy, but also represents the first scientific unification of those disciplines and all other experimental studies of cos- mic processes. NEW DIRECTIONS FOR THE SPACE ASTRONOMY PROGRAM Comparisons with the current NASA space astronomy program reveal some of the new directions which will be required to implement [239] the AMB plan. Perhaps the most significant change is an increased effort in X-ray and gamma-ray astronomy. Less than 10 percent of the current NASA effort, X- and y-ray astronomy amounts to about a quarter of the AMB program, which assigns approximately equal levels of effort to optical, solar, and high-energy astronomy. The increase needed in the minimum bal- anced program is a major start in fiscal year 1971 on a new spacecraft with the point- ing, telemetry, and general sophistication of an Explorer-class spacecraft, but with a payload size capable of carrying large area X-ray detectors, spark chambers, and Cerenkov telescopes, as well as particle and field experiments in the 1- to 5-ton range. Also included is adaptation of a future OAO spacecraft or an equivalent vehicle to carry a state-of-the-art stellar X-ray imaging instrument comparable to existing solar instrumentation. Later, stellar imaging X-ray telescopes of about 1-m aperture, 10-m focal length will be required. The optical ultraviolet astronomy program has a mid-1970's goal of a 1- to 1.5-m tele- scope with diffraction-limited performance, as an essential intermediate scientific and

EXPLORING THE UNKNOWN 615 technological step toward the Large Space Telescope of the 1980's. This could be achieved either through a new spacecraft design or by upgrading an evolutionary OAO program. The infrared astronomy program has a most pressing need for research and develop- ment of detectors and small cooling systems which will permit infrared observations with the much greater efficiency that is commonplace at both shorter and longer wavelengths. Such advances could continue the present high rate of discovery of new classes of astro- physical phenomena from the ground and from airplane observatories. Observations of astrophysical objects in the longwave radio portion of the spectrum with the minimum angular resolution required to distinguish sources may require an antenna made of wires surrounding an area 10 km in diameter. However, a remote possi- bility of making similar observations by “supersynthesis” interferometric techniques must be studied before this large electronically filled aperture is initiated. The continuing need for observations of the solar surface with an effective angular resolution of 5 arcsec will require the development of a ground-controlled solar spacecraft with the instrumental sophistication of the ATM-A. Observations of the planets from Earth orbit will be accomplished with the instru- ments of the planned OAO's and a Small Astronomical Satellite optimized for planetary observations. [240] The acquisition of data on cosmic-ray particles and fields in the interplanetary medi- um requires a careful programing [sic] of small fractions of the missions to the planets, and the joint use of the “heavy Explorer” spacecraft for high-energy astronomy. An important element in the balanced acquisition of essential astrophysical data in the AMB plan is the continuing requirement for the smaller space experiments: the air- craft, balloons, rockets, and small Explorer-class satellites. Though less dramatic and unimposing by their nature, they have a great potential for economic and timely mea- surements of important data that can complement the other space-based and ground-based multiwavelength observations. An essential part of the AMB exercise to project the level of space astronomical research as far as possible into the future was an assessment of the availability and enthu- siastic interest of excellent people-scientists and supporting specialists, including several engineering and technical groups skilled in the measurement of astronomical radiation. Continuity, breadth, and active competition for flight opportunities must be maintained by a strong NASA program in Supporting Research and Technology (SR&T). Both SR&T and NASA's Advanced Research and Technology program must press for- ward to develop essential instrumentation such as lightweight optical mirrors, improved X-ray reflectors and detectors, X-ray photometric standards, electronic imaging systems, improved grating technology, infrared sensors and small cryogenic systems, devices which will be useful in ground based observatories of the future as well as space experiments. Support is also essential for the experimental and theoretical research in related areas of atomic and nuclear physics that will insure progress in analyzing the new observations resulting from these technological advances. In a properly integrated program of federally supported astronomy, NASA should have a responsibility to support particular ground-based instruments, especially those which are most closely and directly related to NASA's mission. Specific instruments, which are of comparable expense to some spacecraft and might be defended as separate line items in the NASA budget, should include special-purpose monitoring telescopes of intermediate (60- to 100-inch) aperture, large optical telescopes in both hemispheres, and a large steerable paraboloid radio telescope.

Document III-16

Document title: NASA Experiment Proposal for Manned Space Flight, Lunar-Surface Ultraviolet Camera, April 1970.

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After initial test flights to the Moon, NASA attempted to maximize the scientific returns of the remainder of the Apollo lunar landing program, when possible inviting scientists to propose experiments to be conducted in the lunar environs. The Naval Research Laboratory (NRL) was successful in receiving NASA approval to fly an astronomy mission to the Moon's surface on the Apollo 16 mission, launched in April 1972. This is an excerpt from the NRL's proposal: a far-ultraviolet camera and spectrograph to be placed on the lunar surface. Under Principal Investigator George Carruthers, an NRL astronomer, the instrument recorded the spectra of many hot stars.

[cover sheet]

TITLE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION EXPERIMENT PROPOSAL FOR MANNED SPACE FLIGHT

LUNAR-SURFACE ULTRAVIOLET CAMERA

EXPERIMENT NUMBER

(A combination of MSC Proposal "Lyman-alpha Ultraviolet Camera," 27 Aug 1969 with NRL Proposal P-11-69 “Far-ultraviolet spectroscopy of Diffuse Background Radiation, Diffuse Nebulae, and Stars, from the Lunar Surface" by George R. Carruthers and Herbert Friedman, dated 14 October 1969.)

PRINCIPAL INVESTIGATOR (Signature) Thornton L. Page (Date)

PRINCIPAL ADMINISTRATOR (Signature) Anthony J. Calio (Date)

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EXPLORING THE UNKNOWN 617 [9] SECTION II. TECHNICAL INFORMATION 1. Objectives: From the lunar surface, outside the Geocorona, to obtain: a. Imagery in the band 1050 - 1230A (mostly Lyman-alpha 1216A) by differencing unfiltered (1050-1600A) and filtered (1230-1600A) photographs, all exposures accurately timed, of: (1) The Geocorona and Earth's Atmosphere, half sunlit (2) Possible clouds of Solar Wind and sky background near the band of the Zodiac at 45° and 135° from the sun, and changes after 5 or 10 hr. (3) Milky-Way star clouds, preferably in Sagittarius (4) Two or three nearby Galaxies, preferably M31, M32, and M33 (5) One or two Clusters of Galaxies, preferably the Coma Cluster b. Spectra in the range 300 to 1600A of: C. (1) Quasars and Seyfert-type galaxies (2) Small, bright galactic nebulae and stars (3) Interstellar extended HII regions (4) Interplanetary gas, zodiacal light, and solar wind near ecliptic (5) Background sky light in Coma Cluster and near pole of ecliptic A valid operational test of optical instruments in the lunar environment. 2. Significance The electronographic Schmidt camera will detect extended surface brightness as small as 0.3 Rayleighs (0.004 erg/sec.m$^2$ sterad at Lyman alpha). Although absorption in the line of sight will complicate imagery and spectra of distant sources, the Lyman-alpha resonance line of hydrogen is an extremely sensitive detector of hydrogen, the most abundant element in the universe. Lyman-alpha emission or absorption indicates the presence of hydrogen gas clouds, and the ratio of its intensity to that of Balmer-alpha 6563A, and of the 21-cm emission line, is related to the density and electron temperature. In normal stellar spectra, there will probably be Lyman-alpha absorption, partly due to cold interstellar hydrogen along the line of sight. Because of the Geocorona Lyman-alpha emission, observations from OAO and from other law Earth-orbiters are limited to relatively bright and compact objects. It is possible that the Solar-Wind clouds emit Lyman-alpha, and that other interplan- etary hydrogen will be detected near the plane of the ecliptic. Away from the ecliptic, interstellar hydrogen should be detected where it is excited by electron collisions or UV starlight. The spatial distribution of Lyman-alpha emission in the Milky-Way is thus relat- ed to the locations of interstellar gas and hot blue stars (Population I). [10] It is possible that very hot hydrogen exists in intergalactic space, and may be detect- ed between the galaxies in clusters. The sensitivity and wide angular field of the elec- tronographic Schmidt camera will show concentrations of intergalactic hydrogen if they exist in clusters, and may thus explain the “Mass discrepancy” in clusters of galaxies. Note that the Coma-Cluster redshift avoids the absorption of its Lyman-alpha in nearby inter- stellar clouds. Spectra will probably include absorption or emission lines at 1165A (CIII), 1206A (SiIII), 123-43A (NV), 1302-06A (OI), 1400A (SiIV) 1550A (CIV), 1610A (Fell), 1134A

618 NASA AND PLANETARY EXPLORATION (NI), 1200A (NI), and possibly lines of CI, CII, and as well as Lyman-alpha 1216A, and can eventually be used to determine chemical abundances in stellar atmospheres, nebulae, the interstellar medium, and the solar wind. Quantitative measurements in this wave- length range will therefore have significance in studies of all these objects, as well as Seyfert-type galaxies and quasars. A slat collimator provides spectra of background light with 30A resolution; with the LiF corrector plate removed from the camera, these should show Lyman-beta (1026A), HeI (584A) and HeII (340A). The latter two, and Lyman-alpha are strongly absorbed by the interstellar medium, but should appear in spectra of the Solar Wind. The operation of a camera-spectrograph on the lunar surface is the first step in tests of how effective an astronomical instrument may be on the lunar surface. This manned operation for 20 or 30 hours should be followed by use of a larger, remote-controlled tele- scope for geophysical and astrophysical purposes for a year or more. If the geo-astrolunar telescope (GALT) proves effective, a larger telescope may be appropriate at a lunar base. 3. Disciplinary Relationship The Geocorona and Lyman-alpha background are related to a decade of research on the Earth's magnetosphere and the Solar Wind, most of it done under NASA auspices. The most recent data were obtained by WEP and Celescope on OAO-A2. The Lyman-alpha emission from nearby galaxies is related to WEP measures from OAO-A2 of far-UV spectra described by Code (1969), and to 21-cm radio measures such as those reported by M. S. Roberts (1967). In connection with the mass discrepancy in clusters of galaxies, there has been speculation by several astrophysicists such as Rood (1969) about intergalactic hydrogen. In each of these areas, there is indirect evidence, but no direct confirmation of the amount and excitation of hydrogen. (It should be noted that Lyman-alpha imagery will provide dramatic photographs of the Earth's environment, and of distant regions of the universe. These are bound to stim- ulate public interest in the geophysics and astrophysics that can be done from the lunar surface.) Two measurements of Lyman-alpha sky background have been made at large dis- tances from the Earth; one by Barth (196) from MARINER V, and one by Kurt and Syunyaev (196) from the Soviet VENURA space probe. Both showed a concentration toward the galactic plane, which indicates that nearby interstellar [11] clouds are not com- pletely black in Lyman-alpha. In fact, Barth found particularly strong emission from the region of the Gum Nebula (RA 8hr. 2 min., dec.-39°55'). Far-UV stellar spectra obtained by Bless and Code (196) from OAO-A2, and by Carruthers (196) from Aerobee Rocket flights, seem to show ten times less Lyman-alpha than predicted from 21-cm radio mea- surements. Kurt and Syunyaev consider that the Solar-Wind protons interact with the mag- netic field of the Galaxy to produce a ring of recombining hydrogen in the plane of the Galaxy far from the sun. The observations proposed here will help sort out Lyman-alpha emission from these several sources, and will determine the changing ionization of the Solar Wind at different distances from the sun. 4. Experiment Approach (See Summary, page 1.) [not included]

 A small electronographic Schmidt camera, shown in Figures 1 and 2 [not included], has been designed and built at the Naval Research Laboratory, and similar units have been flown by Carruthers on three Aerobee Rocket flights. Light is focused by the Schmidt cam- era with LiF correcting plate onto a curved KBr photocathode shaped to fit the focal sur- face. This photocathode, and its opaque backing, are kept at about 20 kV negative with respect to the film cassette, mirror, and rest of the instrument (which is at ground poten- tial, and completely shields the high voltage from the astronaut observer). A lontirudinal magnetic field is provided by bar magnets in the cylinder surrounding the camera, so that the photoelectrons are accurately focused on the film in the cassette (NTB-3 nuclear-track emulsion). This results in a detection efficiency about 20 times higher than the best UV- sensitive photographic emulsions (such as Eastman SC-5). The field of the camera is a 20°-diameter circle; a 27-mm circle on the film at scale 45 arc-min/mm. For direct photography, resolution will be 2 arc-min or better, and the den- sity of the developed film is accurately proportional to the integrated photon flux over a wide range of densities. A sunshade is desirable, even though the camera is to be deployed in the shade of the Apollo LM, to reduce scattered light from the nearby sunlit surface of the moon. A $CaF_2$ filter (or separate corrector plate) is provided to cut out the wavelength band 1050-1230A. The KBr photocathode is sensitive to the band 1050-1600A, and two photographs must be taken to obtain a Lyman-alpha image. Spectra are to be obtained by placing a plane (reflecting) grating in front of the camera as shown in Figure 2. Using a 1200-line/mm replica blazed for 1300A first order, a field of stars or other small sources will produce spectra displaced about 10° from the zero-order (specularly reflected) positions on the focal surface. The film will then record spectra with fairly high efficiency over most of the 20° circular field, cen- tered exactly 90° off the camera axis by proper adjustment of the 3 x 4.3-inch grating. The dispersion is about 75 A/mm and resolution in stellar spectra about 2A. For extended nebulae and sky background, a “venetian-blind" (slat) collimator is [12] nec- essary to provide spectral resolution. Slats about 40 mm wide at 0.2 mm spacing along the grating dispersion limit the field to 20°x 0°.25 and provide spectral resolution of 30A. The camera must be pointed so that this narrow field crosses the target nebula (usually 2° or more in extent), and stars that happen to be in the field are easily dis- tinguished from the nebular spectrum by the limited width of their spectra. The 30-A resolution is adequate for nebulae and background since their spectra are expected to consist of widely spaced emission lines. The lower spectral resolution, set by the slat collimator, makes it unnecessary to have a corrector plate. If this is removed, spectra will extend down to 300A in the extreme UV. We therefore propose to modify the present NRL design to allow 3 choices for cor- rector plate ($CaF_2$ or LiF, or none) and 3 choices for the front end (straight-ahead view through a sunshade, 90° reflection off the grating without collimator, and 90° reflection off the grating with slat collimator). The first selection can best be made by rotating a 6.5-inch wheel with two corrector plates and an empty 3-inch hole in it. The second selec- tion can be made by sliding the sunshade-grating assembly fully up or fully down, and by folding the slat collimator in or out, as shown in Figure 4. Because the astronauts will have difficulty seeing stars through their space suit visors, it is necessary to point the camera by means of setting circles, one in declination (N-S) and one in hour angle (E-W). For objectives a(1-5) and most of b(1-2), pointing accuracy of 5° to 10° is adequate, since the camera field is 20°. For the background-light spectra, objectives b(4-5), the slat collimator requires pointing accuracy of 3° to 5°. A few of the targets for objectives b(1-3) are of about 1° extent in the sky, and the E-W strip field about 0°.5 wide must be pointed within 0°.5 in declination to get their spectra. Moreover, the faint objects require long exposures (up to 4 hours) during which the camera must be turned ("driven") westward at 0°.5 per hour. Hence a drive motor is required on the polar axis shown in Figure 3, and the axis must be parallel to the Moon's axis within 7°. The Moon's axis is inclined to the horizontal by an angle equal to the latitude of the landing site, and the polar axis is so inclined to the “table” in Figure 3. This “table" is to be sup- ported by a tripod that can be levelled using screws on the feet, which may be 10-inch threaded spikes tapped firmly into the soil. After levelling the table, the camera mounting must be rotated until the polar axis points north. This can most easily be accomplished relative to the sun line at the landing site. Because the camera will be set up in the shade of the LM, the second astronaut can walk down-sun out of the IM shadow about 100 feet, where he holds a staff or other tool at arm's length toward the sun with its shadow on his space suit. The first astronaut sets the camera circles at two predetermined settings (both about 90°) and adjusts the mount- ing so that the sighting bar on top of the camera points at the second astronaut's staff when the shadow is directly behind the staff. He then tightens the two lever-screws. fas- tening the mounting to the table with its polar axis within 1° or 2° of the correct direction north. A check on [13] the circle readings is then desirable. They can be set to predeter- mined settings (about 0° on each) to point the camera toward the Earth. A small mirror at the lower end of the almost vertical sighting bar will, show whether the camera is cen- tered on the 2° Earth. If necessary, the settings should be adjusted to center the earth, and the differences in circle settings should be added or subtracted from all later settings in the program of camera targets. After turning on the power supply (from a 28-volt 2-amp-hour battery pack in the cam- era mount, the astronaut selects the proper corrector plate and front end by gently tap- ping lever switches to operate solenoids. He sets the circle settings to predetermined settings and initiates a series of three to six exposures on each target. Care must be taken not to jar the camera tripod. Each exposure sequence starts with moving a new frame of film into position, exposing it 15 seconds, then moving another frame in for a 1-minute exposure, then 4-, 16-, 64-, and 256-minute exposures. After the 4-min. exposure is com- pleted, a small blue light is switched on, after the 16-minute exposure a green light, after the 64-minute one a white light, and after the 256-minute exposure no film transport takes place, and a red light is switched on. Depending on the expected faintness of the target, 3, 4, 5, or 6 exposures will be taken. Then a new corrector plate will be selected by the astronaut, possibly a new front end, and new circle settings. Then he initiates a new expo- sure sequence (which overrides any exposure in process). The three or more exposures ensure the maximum amount of information from each target, since each part of the image or spectrum will reach a density on one of the expo- sures which is on the linear part of the characteristic curve of photographic film. In gen- eral the imagery exposures can be short (0.25, 1, 4, and 16 minutes), while some of the

EXPLORING THE UNKNOWN 621 spectroscopic targets will require long exposures. The program of targets will be planned to fit in with other astronaut activities; it is desirable that the camera be deployed, adjust- ed, and started exposing early in the first EPA. A long exposure should be started at the end of the first EPA since it can continue for 5 hours while the astronauts are resting. Before boarding the LM for the ascent stage, the astronaut must remove the film cas- sette from the camera-spectrograph and carry it aboard for careful stowage (probably in a sealed can) during the return to MSC Houston. The only difficulty anticipated in the procedure outlined above is the astronaut's accurate sighting along the sighting bar attached to the camera. This bar will be designed and tested with astronaut help at MSC. If the desired accuracy cannot be achieved, one or two of the nebular spectra must be omitted. Of course, the astronaut is essential to accomplishing this experiment-in deploying the camera-spectrograph on its tripod, in pointing it with the aid of the setting-circles, in starting the exposure sequence, and in recovering the film for return to MSC Houston. [14] [15] 5. Baseline or Control Data: CÂMERA $1, direct imaging Kär photocathode, 1050-1550A Al + LAF on prinszy mirror #2 CANELA 12, spectra of small objects CSI photocathode, 1050-210OGA. Al + LiF on grating and adrezor #3 I CAMERA +3, spectra of diffuse background photocathode, 300-1550& To corrector plata Pt coating on grating and mirror Slat collinator (HH-13 film and automated film transport in all ommeras) Figure 5. Camaras for Aeroben-150 Trial Flight

622 NASA AND PLANETARY EXPLORATION It would be desirable, though not required, to have simultaneous observations of the Geocorona (inside view) and Solar Wind made from OAO or OGO. The best landing site will be near the lunar equator at the time of first-quarter moon. The best time of year for observing the Coma Cluster and pole of the Galaxy is between April and July. In order to get Solar Wind near time of maximum solar activity, it is desirable to fly this experiment soon (1971). It would be highly desirable to fly three of the cameras with different corrector plates and front ends (as shown in Figure 5) on an Aerobee 150 rocket before the Apollo flight. The purpose of this test flight is not to test instrumental design (which will be fixed by astronaut handling of mockups at MSC) but to check exposure times on various targets, and to learn which classes of targets are most interesting in their far UV spectra. A good test field would be the Constelletion [sic] Orion which has a wide variety of early-type stars, a compact emission nebula (the Orion Nebula), and two extended emission nebu- lae ( Orionis and Hothead Nebula region). The Geocorona Lyman-alpha emission would provide widespread foreground. The NRL can arrange this flight if it is approved, by early 1971 when Orion is visible from the dark site of the Earth. Of course, the data obtained from this first flight would be of scientific value in themselves. Document III-17 Document title: John E. Naugle, Associate Administrator for Space Science and Applications to NASA Administrator, Memorandum and Post Launch Mission Operation Report, May 17, 1971. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Seven years after the team from American Science and Engineering proposed to NASA a long-range plan for the study of x-ray astronomy from space (Document III-8), NASA launched the first satellite dedicated to x-ray astronomy. One of the space agency's many scientific Explorer satellites and the first of its Small Astronomy Satellites, the spacecraft was renamed Uhuru, the Swahili word for “freedom," because it was launched off the coast of Kenya on that country's Independence Day. Uhuru was a pio- neering force in x-ray astronomy, helping astronomers to identify and catalog more than 160 x-ray sources within and beyond our galaxy.

[no page number] EXPLORING THE UNKNOWN 623 Post Launch Mission Operation Report No. S-878-70-01 17 May 1971 MEMORANDUM S/Associate Administrator for To: A/Administrator From: Space Science and Applications Subject: Explorer 42 (Small Astronomy Satellite) Post Launch Report #2 Explorer 42 has been adjudged a success, based upon the results of the mission with respect to the approved prelaunch objectives. As of 12 April 1971, 4 months after launch on 12 December 1970, the SAS-A has com- pleted a full systematic scanning of the galactic plane and a substantially complete scan (95 percent) of the entire celestial sphere. The satellite remains operative with data being acquired in real time at a number of ground stations located around the earth on or near the equator. This planned backup real time mode of operation was initiated after failure of the tape recorder. It permits 60 percent acquisition of each full orbit of data to be obtained and allowed us to achieve the mission objectives. Experiment instrumentation continues to function in an outstanding manner, exceeding many design objectives. The spacecraft control section performance, with the exception of the tape recorder and some decrease in telemetry modulation which has not affected data quality, is excellent. To date, the acquired scientific data has touched on every aspect of observational X-ray astronomy. In addition to the expectation that many more X-ray sources would be discovered, significant unexpected phenomena have also been observed. In particular, the discovery of three new X-ray pulsars, identified as Cygnus X-1, Centaurus X-3, and Lupus X-1, has revealed a completely different class of pulsating X-ray source which differs in many respects from the previously known X-ray pulsar in the Crab nebula. The Centaurus source exhibits an even more startling characteristic in that its pulsation frequency appears to be extremely variable while all known pulsars, optical, radio, or X-ray exhibit no more than a slight variability while consistantly [sic] showing decreases in frequency over time. Some of the initial results have already been submitted to the Astrophysical Journal (letters) and presented to the American Astronomical Society at the annual meeting in Baton Rouge, Louisiana, on 31 March 1971 by the Principal Investigator, Dr. Riccardo Giacconi of American Science and Engineering, Incorporated. The results with emphasis on the Centaurus pulsar has also been presented to the annual meeting of the American Physical Society in Washington, D.C. on 27-30 April 1971. [no page number] The significant results already achieved have been derived solely from quick look data which is only a small fraction of the total amount of data actually acquired. It is expected that the analysis of the production tapes will develop and expand the catalog of known X-ray sources by many more sources than the 20 or so discovered to date. Based upon the results so far, it is probable that further surprises in X-ray source characteristics will appear in the data already acquired and throughout the continued lifetime of the satellite.

624 NASA AND PLANETARY EXPLORATION Dr. Giacconi, in a letter to the Director of Physics and Astronomy Programs discussing experiment performance and scientific results, stated his belief that Explorer 42 “has given us an unqualified scientific success and it has fulfilled and surpassed every expecta- tion we had before launch." [signature] John E. Naugle Document III-18 Document title: Memorandum to Director of Physics and Astronomy Programs, Office of Space Science, from Program Manager, Astronomical and Solar Observatories, Physics and Astronomy Programs, “Status of the Gravitational Physics Program,” April 12, 1972. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. A space-based test of Einstein's theory of relativity intrigued NASA from its inception. With access to the reduced gravity environment of space, scientists might finally be able to test the validity of Einstein's prediction that the passage of time would slow down in a lower gravitational field relative to the passage of time on Earth. NASA's Office of Space Science held discussions with astronomers and clock manufacturers just months after the space agency opened regarding the feasibility of flying a clock aboard a satellite in Earth orbit to test the theory. By the early 1970s three space experiments designed to test relativity seemed possible. This memo describes the three experiments, called Gravity Probes, with which NASA became involved. While Gravity Probe A flew on a sounding rocket in 1976, Gravity Probe C, proposed by the European Space Research Organization, was ultimately can- celled. Gravity Probe B, designed to fly on a satellite, is still in development by NASA. [stamped] APR 12 1972 MEMORANDUM TO: FROM: SG/Director of Physics and Astronomy Programs Office of Space Science SG/Program Manager, Astronomical and Solar Observatories, Physics and Astronomy Programs SUBJECT: Status of the Gravitational Physics Program

EXPLORING THE UNKNOWN 625 NASA is actively engaged in three Gravitational Physics Projects: 1. GP-A, The Smithsonian Maser Clock Experiment 2. GP-B, The Stanford Gyroscope Relativity Experiment 3. GP-C, The ESRO Relativity Experiment These three experiments are described in the attached summary document for Gravity Probes that was prepared for “Proposed FY 73 New Starts" and the individual descriptions of the GP-A, GP-B, [a]nd GP-C Projects. The Gravitational Physics Program was reviewed by a Panel on 12 and 13 October 1971. The Smithsonian experiment was voted Category I unanimously and recommend- ed for flight with the highest priority. It was the consensus of the Panel that both the Stanford and the ESRO experiments were excellent to meet their scientific objectives, and that NASA should continue to support both groups to more clearly define the technical feasibility of the mission. The present status of the Projects is as follows: GP-A: The experiment was selected for flight in late 1971 by Dr. Naugle. The flight project has been approved and is now under active development by the Marshall Space Flight Center (MSFC). The planned launch date is early in 1975. [2] The only uncertainty at the present time, and this is minor, is whether the experiment instrument and the associated spacecraft subsystems can be constrained to about 150 pounds. This weight limitation is imposed by the ability of the Scout vehicle to fly a 10,000nm high trajectory. I expect an affirmative answer to the weight question by the end of April. There are no other problem areas of which I am aware. In fact, Smithsonian is very encouraged by a break through that permits the clock cavity to be cast rather than requir- ing lengthy machining. Further, the ERTS Project will loan MSFC an X-band transponder for initial tests, thus minimizing costs and compacting schedules. GP-B: As you are aware, Stanford has been supported with SRT funds for 8 to 10 years. During this time, they have determined the feasibility of using a highly precise gyroscope (accuracy of 0.001 arc seconds) to determine relativistic effects in low earth orbit (500 nm attitude inclined 90°); they have developed a ground-based dewar; and worked extensive- ly on the gyroscope and the spacecraft control system. In July 1972, BBRC was awarded a Mission Definition Study contract of four months duration. The study, which is now being reviewed at MSFC, indicates the feasibility of the GP-8 mission, provided that the following items are proven: gyroscope, dewar operation in zero gravity, dewar-gyroscope operation in zero gravity, and optical contacting for assembling the telescope and gyroscopes. The gyroscope is being developed at both Stanford (M-H contract) and MSFC. Recently, Stanford has demonstrated the levitation of the gyro rotor, and by June 1 expect that complete gyro operation in a 1-g field will be demonstrated at either or both Stanford and MSFC. A Cryogenic Workshop was held at MSFC in March to determine the state of the art in cryogenic systems at liquid helium and liquid hydrogen temperatures, and to attempt to permit a coordinated attack on the requirements of the planned and potential uses of cryogenic systems. I expect that recommendations resulting from the Workshop will be available in the next one to two months. This should provide a mechanism for developing a dewar for the Stanford experiment. [3] MSFC will take over the responsibility for the Stanford SRT effort in FY 1973. Present plans call for a $625K GP-B SRT budget at MSFC in FY 1973, of which $325 is earmarked for Stanford. The SRT support will continue until a flight project is approved in either FY 1974 or FY 1975. The earliest launch date would be the late 1970's. GP-C: ESRO has been constrained in their Solar Probe Experiment to funding for studies. In the past two years, they have studied the mission feasibility, the laser clock, the X- and S-band transponders, and a number of related items. Although they would like to do laboratory work on the drag-free system required by the experiment, no funding has been available. As you know, NASA is committed to aid ESRO in the Mission Definition. This com- mitment has resulted in reviews of the studies by MSFC, JPL, and Headquarters person- nel, and participation in their Mission Definition Group meetings in Europe. A year ago ESRO wanted NASA's cooperation for a Titan vehicle and in-orbit opera- tions support. Now, in addition, I understand they plan to discuss with Dr. Naugle on 18 April 1972 the possibility of further cooperation (maser clock, X- and S-band transpon- ders, and perhaps lasers). The additional support is brought about by the level of their scientific budget ($25 to 30M per year) and the present estimate of the GP-C mission of $50 to 100M which they probably cannot fund alone. They are also seeking cooperation from Germany with the use of the HELIOS spacecraft system. The future of this program is, in my mind, less firm than the GP-B mission, both from the technical and the funding standpoint. Technically, they will have to begin demon- strating the feasibility of systems, particularly the drag-free system, as we have done with the gyro experiment. In the funding area, they need help from outside ESRO. ESRO has been shooting for a luanch [sic] in the late 1970s. In summary, we are moving out with the GP-A mission. Both the GP-B and the GP-C missions are uncertain and do have technical areas that require feasibility demonstration. [4] You should also keep in mind that MSFC, under Dr. Decher, is undertaking a com- parative study to determine the relative merits of the various methods now being used or under consideration (ground-based efforts by MIT and JPL, GP-B, and GP-C) to deter- mine the relativity parameters ■ [Beta] and y [Gamma] and the solar quadruple moment J2. This study will probably not be completed for one year. It will involve all or the major- ity of the groups working in this area. C. Dixon Ashworth Enclosure [not included]

EXPLORING THE UNKNOWN 627 Document III-19 Document title: Space Shuttle Payload Planning Working Groups, Goddard Space Flight Center, Final Report, Volume 1: Astronomy, May 1973. Source: Nancy Grace Roman, personal collection, reprinted with permission. Document III-20 Document title: Interim Report of the Astronomy Spacelab Payload Study, Astronomy Spacelab Payloads Project, NASA, July 1975. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. With President Nixon's January 1972 decision to pursue the development of the Space Shuttle as NASA's next centerpiece project after Apollo came the need to define the purposes it would serve. Like their counterparts focusing on other disciplines, the working group examining astronomical uses of the Shuttle determined that the new vehicle could serve a number of functions. Such purposes ranged from flying astronomical instruments for the duration of a Shuttle mission, to enabling astronauts to launch and service the Large (later Hubble) Space Telescope. The contribution to the Space Shuttle program by the European Space Research Organization (suc- ceeded by the European Space Agency in 1975) of Spacelab, a scientific facility that could be flown in the Shuttle's payload bay, provided yet another way in which astronomers could take advantage of the Shuttle. Many astronomers believed the frequency of Shuttle flights anticipated (two per month) com- bined with Spacelab's versatility would offer them a cost-effective and readily available means to fly their instruments in space. The 1975 report enumerates the astronomical uses and required subsys- tems for instrument integration identified by a NASA working group created to assess Spacelab's value to astronomy. Astronomers used the Spacelab facility on several occasions in the 1980s and 1990s with great success. [cover sheet] Document III-19 FINAL REPORT OF THE PAYLOAD PLANNING WORKING GROUPS Volume 1 Astronomy

628 NASA AND PLANETARY EXPLORATION MAY 1973 NATIONAL AERONAUTICS & SPACE ADMINISTRATION GODDARD SPACE FLIGHT CENTER Greenbelt, Maryland 20771 [xv] ASTRONOMY WORKING GROUP EXECUTIVE SUMMARY The principal advantages of space astronomy over ground-based observations reside in the greatly increased spectral coverage and angular resolution attainable from above the earth's atmosphere. For the first time celestial objects can be studied over virtually the entire electromagnetic spectrum from radio to gamma-ray frequen- cies. Even at the present early stage, this ability has produced a number of major sur- prises-for example, the overwhelming infrared emission from a variety of objects including planetary nebulae and galactic nuclei. Higher angular resolution will not only permit more detailed study of the structure of individual objects but, because of night sky suppression, will also allow observation of substantially fainter and hence more distant sources. By exploiting these advantages during the coming decades we will be able to solve, or at least to greatly increase, our understanding of such major sci- entific problems as the evolution of the early universe, the nature of quasars, galactic nuclei and radio sources, the formation of galaxies and of the stars within them, the origin of the chemical elements, and the origin of the solar system and of life itself. Solutions to these problems will impact all branches of human endeavor that have been seriously hampered in the past by the limited view of the universe available from the ground. The immense potential of space astronomy has been amply demonstrated during the last decade with comparatively small, exploratory instruments, limited to the observation of relatively bright sources. The time is now appropriate to establish in space the full range of observing facilities required to solve longstanding astronomical problems. The advent of the Space Shuttle renders this not only technically feasible but even moderately inex- pensive as compared to earlier ventures in space science. The cornerstone of our recommendations for the 1980s is the Large Space Telescope (LST), a three meter aperture, diffraction-limited telescope optimized for the ultraviolet and visible regions of the spectrum but usable also in the infrared. It will be operated as an automated satellite and will be periodically serviced by the Shuttle. The LST will extend significantly the distance to which we are able to probe the universe and offers, for example, a prospective solution to the cosmological problem, which has not proved pos- sible from the ground. A balanced program requires that this major instrument be sup- plemented by other more specialized instruments, as indeed are also required in ground-based observatories. [xvi] Because the LST is not planned primarily for the infrared, early emphasis in the Shuttle Sortie program is placed on this spectral region. Two infrared telescopes are pro- posed. A 1.5-meter aperture telescope, cryogenically cooled to about 20°K specifically for the 10-50 mm wavelength region.

EXPLORING THE UNKNOWN 629 A very large uncooled telescope for the far-infrared and microwave region, and for planetary studies and narrow-band spectroscopy over the whole infrared range. Although both telescopes could operate as automated free-flyers based on the same spacecraft Support System Module (SSM) developed for the LST, both would gain by operation on the Shuttle. For the uncooled telescope the Shuttle allows the accommoda- tion of larger optics than would be possible with the Titan-compatible SSM, as well as the possibility of interchanging instruments at the focal plane during flight. The cryogenic sys- tem for the cooled telescope would be much simpler and less expensive on the Shuttle. These telescopes will be powerful tools in the exploration of such diverse phenomena as the immense infrared energy output of galactic nuclei, the conditions in the interstellar medium leading to star formation, and the physical properties and composition of plane- tary atmospheres and surfaces. In the ultraviolet, there is a definite need for a wide angle telescope to provide a UV survey in one broad wavelength band if the LST is to be used for many years to maximum effect. Subsequent use for studies at different wavelengths or for an ultraviolet spectral sur- vey would be valuable but less urgent. A one meter diffraction-limited telescope for the ultraviolet and visible will provide high angular resolution imaging over relatively wide fields of view (0.5°). Such a capability is required, for example, for photometric studies of stellar evolution in globular and open clusters and to supply observations of nearby galax- ies as the basis for LST studies of faint (> 21m) extragalactic sources. Unless or until the LST makes possible the frequent monitoring of solar system bodies, the 1-meter telescope can provide the needed synoptic coverage. The major advantage of the Shuttle for both these instruments is that it will allow use of photographic and electronographic detectors with their very large information storage capability. The 1-meter telescope will also provide an important test bed for auxiliary instrumentation for LST, allow specialized observations of a “one-of-a-kind” nature and relieve LST of observations of relatively bright sources. In addition to these five instruments, which the panel considered in detail, several other instruments which were considered briefly are typical of those which the Shuttle program should include. Examples are a very wide angle ultraviolet camera for the study of large scale, low surface brightness nebulae and star [xvii] clouds, a grazing incidence telescope for the extreme ultraviolet between the normal X-ray region and the Lyman limit of hydrogen, Explorer-class free flyers (to measure the cosmic microwave background for example), and rocket-class instruments which can fly fre- quently on a variety of missions. Except for the LST, each of the major astronomy instruments requires approximate- ly half of the space, weight, and other support of a Sortie flight. While each could be oper- ated remotely from the ground, our present impression is that in most cases it would be preferable to have the support of a four man Shuttle crew, in addition to the pilot and co- pilot, and a small laboratory to provide workspace, data storage, communications and access to the focal plane of at least one telescope. Although the individual instruments could share a Sortie mission with another discipline, compatibility requirements are severe. Astronomy requires stabilization of the Shuttle to near one arc minute (by means of control moment gyros), control of the pallet pointing direction throughout operation as dictated by the astronomical program, and a contamination-free environment. We

630 NASA AND PLANETARY EXPLORATION therefore believe that we would be our own best companion. Most scientific direction must be from the ground, making it necessary to have excellent communication, includ- ing picture transmission, on both up and down links. A data relay satellite would be very helpful, although astronomy can use the intermittent communication provided by a ground network of tracking stations if adequate capacity compensates for limited time and if real-time communications are possible from the receiving station to a central control station at the same rate. Document III-20 [cover sheet] INTERIM REPORT OF THE ASTRONOMY SPACELAB PAYLOADS STUDY Executive Volume Prepared by the Astronomy Spacelab Payloads Project JULY 1975 NATIONAL AERONAUTICS & SPACE ADMINISTRATION GODDARD SPACE FLIGHT CENTER Greenbelt, Maryland ********** [51] CONCLUSIONS At this stage of the Astronomy Spacelab Payload Study, several conclusions about astronomical investigations and the effective methods of using the Spacelab for research in astronomy during the early 1980s have been identified. In each of the scientific areas of the study, solar physics, UV and optical astronomy, and high energy astronomy, a sub- stantial and valuable scientific program has been identified based on the experience of our past research in space, from recommendations from available studies and from con- sultations with scientists in the fields. The direct utilization of instruments operated from balloons, sounding rockets and satellites appears readily feasible and, in many cases, desir- able in the pallet mode of the Spacelab missions. Furthermore, the huge volume and weight available with the Space Shuttle affords the opportunity of incorporating large instruments and, in fact, facilities in the Spacelab program. The costs for the design and construction of such instruments for use with Spacelab appear very reasonable; signifi-

 cantly less than instrument costs used in satellite payloads as the development of these instruments in many ways appears to parallel the techniques used with sounding rockets, balloons and aircraft. The methods of carrying out experiments with Spacelab are of a special nature with many similarities and disparities with the past techniques. Although the Spacelab missions represent full scale satellite-of-the-Earth operations, the missions are relatively shortlived, they may be amended by the crew of specialists on hand, and the return to Earth of the scientific equipment for maintenance and modifications is a guaranteed aspect of this mis- sion mode. In addition, the flight-into-orbit schedule is like the streetcar approach of the old Orbiting Geophysical Observatory, with an expected launching schedule of two space shuttles a month and probably about ten launches a year which may be available for some astronomical research. In effect, in about five years from now, the capacity for carrying instruments into Earth orbit will be increased by more than an order of magnitude and certainly more than the increase in the number of scientists, funds and other resources for carrying out research. It is essential that the methods for utilizing Spacelab match and adjust to such constraints. The Astronomy Spacelab Payloads Study has, from the engineering and mission analysis investigations, found several requirements to effectively use the Spacelab for astronomy. These requirements include a set of pointing platforms for a variety of instru- ments, special instrument containers for rapid and easy integration of scientific instru- ments, some standardization of power, telemetry and operational functions, and modular overall integration into pallets at the integration center for the scientific program. The conclusions so far derived from this study are listed below. They are divided into groups defined by scientific areas and by required subsystems to integrate the scientific instru- ments and by the cost of such integration and schedule procedures. [52] Scientific Program 1. Astronomers may have available simple and regular access to extended wave lengths into ultraviolet, superb image quality and a dark sky with a one meter class Spacelab UV Optical Telescope (SUOT). This ultraviolet facility can provide regular opportu- nities for a great number of astronomers, and with the wide field and regular access to focal plane instruments it would complement the Large Space Telescope. The SUOT should be developed for early Spacelab operation in 1981. 2. A solar telescope of large aperture for diffraction-limited observations extending over near UV and visible wavelengths can be of great value in studies of the heating of the solar chromosphere, for studying mass transport, magnetic field configurations, fine scale phenomena in sunspots and abundance distributions of elements in solar struc- ture. Such a spectroheliograph or One-Meter Telescope Facility should be developed for the 1980-1981 Spacelab program in solar physics. 3. A Solar EUV-XUV Soft X-ray Facility covering the solar spectral region from 2000Å to 2Å and a Hard X-ray Imaging Facility consisting of instruments to study X-ray, gamma ray and neutron emissions from the flaring and nonflaring sun, should be construct- ed for the early 1980 period of Spacelab operations. These facilities will be used for observations and studies of processes in the tenuous transition region and the coro- na, and studies of the physics of flares.

 4. The field of high energy astrophysics encompassing X-ray, gamma ray and cosmic ray astronomy includes an outstanding group of scientists with the developed technolo- gies, instrumentations and experiments that can fully utilize the expanded capability of the early Spacelab modes. One of the first Spacelab missions should be devoted to high energy astrophysics and regular opportunities for about two dedicated missions a year should be planned. 5. A wide variety of experiments derived from experiments using sounding rockets, balloons and satellites have been identified in each of the astronomy disciplines. Considerable flex- ibility exists in combining experiments and integrating instruments on pallets and seg- ments of pallets and these experiments are compatible with many Spacelab missions. An organized instrument preparation, integration and scheduling system for effectively and fully using each Spacelab mission would give scientists a powerful, productive and contin- uing means for carrying out research in astronomy and astrophysics. [53] Experiment Integration and Mission Management Operations 1. Three classes of pointing systems have been identified to fulfill the scientific require- ments for astronomical observation with Spacelab. (1) For facilities and large high energy instruments, the Instrument Pointing System (IPS) using an inside-outside gimbal, is under development by the European Space Agency. A pointing accuracy and stability in the one arc sec- ond range with limited roll is required for solar and astronomical observa- tions. For several of the X-ray experiments more modest, near one arc minute pointing, and instrument capacities of close to three tons are needed. Based on the preliminary projected scheduling of this pointing system for astrono- my and applications, a total of three (3) IPSs are required. (2) For pointing instruments of moderate weight a double-mount Small Instrument Pointing System (SIPS) has been under study. The SIPS can accommodate the moderate weight ATM class of solar instruments and the great majority of solar and astronomical instruments with a pointing accura- cy and stability approaching the one to two arc second range. Four SIPS units are required for astronomy. (3) A low-cost, one arc minute accuracy and 10 arc second stability system is need- ed for the many rocket-class instruments. This system may readily be devel- oped in-house by personnel of the Sounding Rocket Division of GSFC. Six of these units are needed. 2. Instrument canisters are required for thermal control and ease of integration of the wide variety of instruments considered for Spacelab astronomy flights. Canister con- figurations for compatibility with the SIPS and various instrument and mounting requirements can be developed. Contamination control is available with the instru- ment canister. The flexibility of the instrument canister is substantial, as it not only is used to control the environment of the instrument, but it also may afford a means of remote integration and becomes a shipping container for the instrument on Earth and in space. 3. Astronomical research with Spacelab involves mission planning and scheduling, instrument integration and mission operations, and requires Payload Operations

EXPLORING THE UNKNOWN 633 Control Center (POCC) at the GSFC. The experimenters would use the POCC dur- ing the installation and check out of instruments on pallets and later during the oper- ation of the instruments in orbit. The POCC would incorporate in-flight experiment operations, Spacelab communications, and data reduction operations. Investigator Stations would be incorporated into POCC for the operation and control of individ- ual and sets of experiments during the mission. [54] 4. For Spacelab mission planning, the assignment of prime mission goals to a partic- ular astronomical discipline, a “dedicated mission,” is scientifically and operationally efficient because the orbit, orientation, and mission sequences may be optimized. Solar physics, UV/optical astronomy and High Energy Astrophysics are generally mis- sion compatible and combinations of experiments in these fields also would be sci- entifically productive. The interrelationships among mission parameters are complex and necessitate iterative and continuing mission analyses studies and operations. The Astronomy Spacelab Payload Study has identified the mode for astronomical research using scientific facilities and instruments evolved through research using sound- ing rockets, balloons, aircraft, and satellites and the large instruments and instrument evo- lution making use of the Space Shuttle capacity and instrument return capability. The use of the pressurized module, the interface with free-flyers and space stations, and the gen- eral effects of working with the Spacelab mode requires further study. Of special concern is the ordering of the developments of facilities, the focal plain instruments and the sup- port for experiments for the early missions. Although the actual selection of experiments will be made from proposals submitted according to the NASA Announcements of Opportunity, early guidance in the relative value and comparison factors for the scientific and technological program is required. This is the initial year for Astronomy Spacelab Payload Study—in the next year the start and the ordering of the facilities will be made, the critical engineering subsystems for pointing, environment, power and data handling will be under development and the eval- uation of experiment proposals and the selection of early experiments will be initiated. The newly evolving capabilities of the Space Shuttle will not only permit a new approach to scientific investigations, but can influence lowering the costs of scientific instruments and their supporting subsystems. The availability of the shuttle as an Engineering test bed, the substantial payload carrying capacity, the presence of man in the operation and the capability to return the instruments should permit the development of ASP payloads in an evolutionary manner and enable the scientist and engineer to take risks. Cost savings should be expected. In addition the capability to refurbish and fly pay- loads should further increase the cost effectiveness of the ASP payloads. To take full advantage of this new potential, cost consciousness and constantly look [ing] for the “cost drivers" will continue to be a prime concern.

634 NASA AND PLANETARY EXPLORATION Document III-21 Document title: High Energy Astronomy Observatory Project Plan, NASA, June 13, 1973. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. While ultraviolet astronomy dominated NASA's interest in the early days of the space program, the results of the gamma-ray and x-ray experiments carried aboard spacecraft during the 1960s and con- ducted from the ground expanded the popularity of high-energy wavelength studies among astronomers. Just as NASA had developed a program of large spacecraft, the Orbiting Astronomical Observatories, to explore the optical wavelengths, in the early 1970s the space agency initiated a series of multi-ton High Energy Astronomical Observatories (HEAOs) dedicated to gamma-ray and x-ray astronomy. After providing initial funding for the first two of three planned HEAOs in 1971, NASA suspended the program in early 1973 due to money shortages in the space program. This document portrays the state of the program as it underwent restructuring to accommodate the funding changes. In the end, NASA managed to fly three HEAO spacecraft, albeit less ambitious in scope than those originally planned; none of the HEAO missions planned for the Space Shuttle were flown. HMA- 1001 June 13, 1973 APPROVED: [signature] Rocco A. Petrone Revision C HMA-1001 HIGH ENERGY ASTRONOMY OBSERVATORY Director, Marshall Space Flight Center [iii] PROJECT PLAN APPROVED: [signature] J. Naugle Associate Administrator for Space Science FOREWORD This document is the agency plan for conducting the activities associated with NASA Flight Project 832, High Energy Astronomy Observatory (HEAO). This plan is prepared and maintained in accordance with NMI 7121. 1B, “Planning and Approval of Major Research and Development Projects,” (dated July 1, 1972), and the proposed draft of NMI 7120. 1A, “Authorization and Control of Space Science (OSS) Research and Development Projects." This document describes the overall plan and approach, and is the basic agreement between the Associate Administrator, Space Science, and the Director, Marshall Space

EXPLORING THE UNKNOWN 635 Flight Center for proceeding with the HEAO project. This plan is the basis for all project and lower level detail planning necessary for project operations, and is to be followed by all involved NASA organizations. It has been revised to reflect the agency decision to restructure the HEAO program to achieve most of the scientific objectives through a lower cost approach over a longer period of time. The restructured program consists of two groups of missions, designated Block I and Block II. Block I missions utilize conven- tional medium class launch vehicles while Block II concepts utilize Space Shuttle capabil- ities and approved experiments not assigned to Block I missions. Detailed planning as reflected herein addresses only Block I missions due to the preliminary nature of the sec- ond block. The planning will be further expanded at significant points in the life cycle to incorporate current project experience. This plan supersedes prior revisions in their entirety. The document is prepared and maintained for OSS by the MSFC HEAO Office in coordination with the OSS Program Office. The document will be updated when the degree of content change is sufficient to justify a new issuance. Proposed changes to this plan shall be submitted to the MSFC HEAO Office for coordination and staffing for management approval. [1-1] A. GENERAL ************* SECTION 1 - INTRODUCTION This document contains the overall plan for proceeding with the first group of mis- sions (Block I) established for the NASA project identified as: NASA Flight Project 832, entitled “High Energy Astronomy Observatory (HEAO).” The NASA code number is 85-850-832. B. PROJECT AUTHORIZATION The HEAO Project was initially established and authorized as one of the projects of the Physics and Astronomy Program by Project Approval Document (PAD) 71-85-001 dated July 2, 1971. The HEAO project was further delineated in Enclosure 6 of that FY 71 PAD. The PADS concerning the HEAO Project which had been issued as of the date of this plan are listed in Table 1-A in chronological order: TABLE 1-A CHRONOLOGY OF AUTHORIZATIONS 1. PAD 71-85-001, “FY 1971 Project Approval Document, Research and Development" and its Enclosure 6, both dated July 2, 1971. 2. PAD-85-850-P&A, “Project Approval Document, Research and Development," and its enclosure 6, both dated November 2, 1972. 3. PAD-85-850-P&A, “Project Approval Document, Research and Development," and its enclosure 6 both dated (TBD). ******** [1-3] C. PROJECT DESCRIPTION The Physics and Astronomy Program is primarily directed to extend the present knowledge of the earth's space environment, the sun, the stars, and the more distant celes-

636 NASA AND PLANETARY EXPLORATION tial bodies. This research is being conducted through a combination of various tasks such as Supporting Research and Technology and flight projects such as HEAO. The HEAO Project will search for and obtain high resolution data concerning high energy radiation from space (i.e., celestial X rays, gamma rays, and cosmic ray flux) by means of large unmanned earth orbiting observatories which will be built, launched, and operated as independent missions with complementary mission objec- tives and scientific experiments. The HEAO Project as presently contemplated is divided into groups of missions called “blocks." Block I observatories use the Atlas/Centaur as the launch vehicle. Block II would use the Space Shuttle capabilities with the observatories containing experiment hardware which could not be accom- modated in Block I. Block I consists of three missions, designated HEAO-A, HEAO-B and HEAO-C. The basic elements of Block I are shown in Figure 1-1 [no figures included]. HEAO-A is a scan- ning mission which will conduct a total sky survey for X-ray sources. HEAO-B is a pointing mission which logically continues the program by using an X-ray telescope to accurately locate, define, and determine the properties of the major X-ray sources.. HEAO-C is a scanning mission surveying the sky for gamma ray and cosmic ray. Figure 1-2 and 1-3 illus- trate the current observatory configurations for HEAO-A and HEAO-B. The HEAO-C configuration is being defined using candidate experiments to formulate the payload, hence an illustration is not shown. ******** [1-6] D. PROJECT STATUS The HEAO program as initially approved was suspended by an agency decision on January 5, 1973. The suspension is expected to remain in effect for approximately one year, during which time the previously planned program will be restructured and rebaselined as described herein. A recommended approach for restructuring the pro- gram was presented to the Associate Administrator for Space Science, on February 13, 1973, and then to the Administrator of NASA on February 20, 1973. Authorization to proceed with the redefinition and to establish firm cost and schedule plans was issued by the Office of Space Science (OSS) on March 5, 1973. OSS assigned experiments to missions HEAO-A and HEAO-B, and determined the candidate experiments to be con- sidered in defining the HEAO-C observatory. Redefinition of the selected Block I mis- sions has been initiated, and revised proposals are being prepared. Preliminary and conceptual design is underway. Definition of Block II payloads is proceeding at a low level of effort, pending clarification of the overall definition approach and development of funding plans. [2-1] A. GENERAL SECTION 2 - PROJECT PLAN SUMMARY This section summarizes the approaches and planning to be used in accomplishing the HEAO Block I missions. Each of the sections following this summary contains the detail necessary to provide a complete agency plan for the project.

EXPLORING THE UNKNOWN 637 B. PROJECT OBJECTIVES The objective of the HEAO program is to extend the present knowledge of celestial X-rays, gamma rays, and cosmic-ray flux through studies facilitated by means of large earth-orbiting observatories. The objective of the X-ray studies is to survey the entire sky for X-ray sources of about one-millionth of the intensity of the brightest known source, SCO X-1, and to investigate the shape and structure of these sources. Many sources show flares and flickering; the observatories will monitor these intensity variations. The initial survey mission will be fol- lowed by missions capable of performing studies on the spectra, structure, and location of these sources. The gamma-ray studies will be directed at the measurements of the gamma-ray flux and at determining source locations. Line spectra will be obtained and analyzed from the sources discovered. These studies, along with the X-ray studies, should contribute to our understanding of such phenomena as pulsars and quasars. The high energy particle experiments will examine the composition and synthesis of cosmic-ray nuclei. The isotopic composition of cosmic rays will provide information on the age and nuclear interactions producing the rays. The existence of very heavy nuclei will provide [2-2] an opportunity to probe into their origin, age and propagation through the interstellar medium. These studies will form the basis for future orbiting cosmic-ray laboratories, utilizing the capabilities afforded by the Space Shuttle. The objective will be achieved incrementally on an integrated basis by the HEAO mis- sions. Each mission is planned to achieve certain goals and to provide information which can be utilized in subsequent activities to achieve the project objectives. Section 3 [not included] describes the project and mission objectives in detail. Document III-22 Document title: J. Mather, Goddard Institute for Space Studies et al. "Cosmological Background Radiation Satellite," October 1974. Source: John Mather, Goddard Space Flight Center, NASA. One of the most important astrophysical measurements is that of the Cosmological Microwave Background (CMB), the remnant of the radiation resulting from the “big bang" at the origins of the universe. Because of the expansion of the universe in the 13-15 billion years since its origin, this orig- inally very hot radiation was thought to now be only a few degrees above absolute zero. The Cosmological Background Explorer (COBE), first proposed in 1974 and launched in 1989, gathered data of fundamental scientific importance on the CMB.

638 [cover sheet] [i] NASA AND PLANETARY EXPLORATION COSMOLOGICAL BACKGROUND RADIATION SATELLITE J. Mather P. Thaddeus Goddard Institute for Space Studies R. Weiss D. Muehlner Massachusetts Institute of Technology D. T. Wilkinson Princeton University M. G. Hauser R. F. Silverberg Goddard Space Flight Center OCTOBER 1974 COSMOLOGICAL BACKGROUND RADIATION SATELLITE INVESTIGATORS AND INSTITUTIONS John C. Mather 212-678-5609 Patrick Thaddeus 212-678-5621 Goddard Institute for Space Studies 2880 Broadway New York, New York 10025 Rainer Weiss 617-253-3527 Dirk Muehlner 617-253-4824 Massachusetts Institute of Technology 20F006 Cambridge, Massachusetts 02139 David T. Wilkinson 609-452-4406 Princeton University Department of Physics, Jadwin Hall Princeton, New Jersey 08540 Michael G. Hauser Robert F. Silverberg 301-982-2468 301-982-2468

EXPLORING THE UNKNOWN 639 Infrared Astronomy Research Program Laboratory for High Energy Astrophysics Goddard Space Flight Center Code 661 Greenbelt, Maryland 20771 [ii] TABLE OF CONTENTS Proposers and Institutions Table of Contents I. Investigation and Technical Plan A. Summary B. Objectives and Significant Aspects C. Plan of the Report Table 1. Cosmological Background Radiation Experiments D. Spectrum of the 2.7°K Cosmic Background Radiation from 0.1 to 3 mm Wavelength 1. Introduction a. Objectives b. Expected Results C. Instrument Introduction d. Satellite Requirements 2. Scientific Context a. The 2.7°K cosmic background radiation spectrum b. Interstellar dust clouds C. Infrared galaxies 3. Review of Experiments to Date a. 2.7°K Cosmic Background b. 0.1 0.3 mm Background 4. Limitations of Non-Satellite Methods a. Ground-based and balloon-borne Table 2. Measurements of the 2.7°h Background from 0.3 to 3 mm b. Rockets C. Indirect Measurements 5. Why a Satellite Experiment 6. Investigative Approach 7. Instrument Description 8. Parameters and Spacecraft Requirements 9. Design Considerations During Study Phase E. Isotropy of the 2.7°K Cosmic Background between 0.5 and 3 mm Wavelength Introduction 1. a. Objectives [iii] b. Results Expected C. Instrument d. Spacecraft Requirements i 1 2 2 2-T 3 33 3 4 4 4 4 6 6 6 6 7 7 7 7-T 10 860 9 10 10 12 13 14 23 1 14 14 14 14 14

640 NASA AND PLANETARY EXPLORATION 15 16 66771 19 19 2. Scientific Context 3. Review of Experiments 4. Limitations of Non-Satellite Methods 5. Need for a Satellite 6. Instrument Description 7. Spacecraft Requirements F. Isotropy of the 2.7°K Cosmic Background at 3, 5, 9, and 16 mm Wavelength 1. Introduction a. Objectives b. Results Expected C. Instrument d. Satellite Requirements 2. Scientific Context and Current Experiments [iv] 3. 4. 5. 6. Limitation of Non-Satellite Methods and Need for a Satellite Experiment Concept Instrument Description Data Analysis and Results Expected Table 3. Radiometer Noise Limitations G. Search for Diffuse Cosmic Radiation at 5-30_ Wavelength Introduction 1. a. Objectives b. Results Expected Instrument 222222 2225 23-T 24 24 24 24 C. 24 d. Spacecraft requirements 25 2. Scientific Context 25 3. Review of Experiments to Date 27 4. Why a Satellite Experiment 27 5. Instrument Description and Performance 28 6. Spacecraft Requirements 29 H. Spacecraft Description 30 I. Guest Investigators 32 II. Management and Cost Plans 33 A. Management Plan B. Cost Plan 33 35 References Figures III. APPENDIX 37 38 49 1. Space Cryogenic System (Ball Brothers Research Corp.) 2. Principles of Operation of the Polarizing Michelson Interferometer 3. Biographies AI-1 AII-1 AIII-1

 [no pagination] A. Summary A group of four instruments to measure the cosmological background radiation is proposed for a Delta-class Explorer. The experiments address fundamental issues in obser- vational cosmology. Three of the experiments deal with the 2.7° K cosmic background radiation. The first is a definitive measurement of the spectrum of this radiation between 0.1 and 3 mm using Fourier transform spectrometry. The experiment will map the spec- trum at shorter wavelengths than have been possible from balloons and will measure the spectrum in the region around the blackbody peak with a precision of 10-4. It will also look for the emission from cold dust clouds and from infrared galaxies. The second and third experiments are devoted to measuring the large scale isotropy of the background radiation at a number of wavelengths to a precision of 10-5. It should be possible to mea- sure the motion of the Earth relative to the co-moving frame defined by the expansion of the Universe. Measurements at several wavelengths are required in order to distinguish anisotropy in the background radiation itself from anisotropy due to discrete sources. Definite observation of the Earth's motion relative to this radiation will be further confir- mation of the primeval fireball interpretation of the 2.7° K radiation. The fourth proposed experiment searches for diffuse radiation in the 5-30 micron wavelength range, expected to arise from interplanetary dust, interstellar dust, and, in particular, from the integrated luminosity of very early galaxies. The experiment is designed to separate these contributions by their spectral and directional properties. These four experiments have similar spacecraft requirements. Three require liquid helium, and two require slow rotation. The required scan of the sky can be provided by the orbital motion combined with precession of the orbital plane. The spacecraft could be shared with other experiments requiring near vertical pointing and the same simple scanning mode. The scientific importance of these experiments, their need for a space platform, and the relatively modest spacecraft requirements they impose all recommend this mission as an attractive first application of a liquid helium cryostat in space. B. Objectives and Significant Aspects An Explorer spacecraft equipped with cryogenically cooled instrumentation will pro- vide a uniquely sensitive system for study of diffuse cosmic radiation. It is proposed to develop a mission in which such a system is used to make definitive measurements on the radiative relics of the earliest stages of the universe. Four experiments are proposed, char- acterized by their common cosmological motivation and by compatible and relatively modest demands upon the spacecraft. The experiments proposed here include: 1. Spectrum of the 2.7 K Cosmic Background from 0.1 to 3 mm 2. Isotropy of the 2.7 K Cosmic Background between 0.5 and 3 mm Wavelength 3. Isotropy of the 2.7 K Cosmic Background at 3, 5, 9, and 16 mm Wavelength 4. Search for Diffuse Cosmic Radiation at 5-30 micron Wavelength. The personnel responsible for each experiment and principal requirements for each are summarized in Table 1. It should be noted that experiment (3) does not require cryo- genic cooling, but it is intimately related to the first two experiments, and does require a satellite platform for high quality results.

642 NASA AND PLANETARY EXPLORATION C. Plan of the Report In order to facilitate understanding of each experiment, the remainder of Section I discusses the objectives, concept, and spacecraft requirements for each experiment sepa- rately. It should be emphasized, however, that this separation is only for convenience: we strongly believe that this mission should be considered as a whole, since it represents a sci- entifically exciting and technologically modest first application of a cryogenic satellite. To this end, a technical plan providing for a suitable spacecraft and orbit for the complete mission is also presented in Section I. Management and cost plans for the mission are given in Section II. Appendix I contains a summary of the current status of cryostat devel- opment prepared by Ball Brothers Research Corporation. The operating principles of the Michelson interferometer used in experiment (1) are discussed in Appendix II. Biographies of the proposers are contained in Appendix III. Table 1 Title Description COSMOLOGICAL BACKGROUND RADIATION EXPERIMENTS Spectrum of the 2.7°K Cosmic Background from 0.1 to 3mm Wavelength Polarizing Michelson interferometer, 0.1 to 3 mm range, liquid helium cooled Isotropy of the 2.7°K Cosmic Background Wavelength Broad-band radiometer 3mm to 0.5mm, liquid helium cooled detector Isotropy of the 2.7°K Cosmic Background at 3, 5, 9, and 16mm Wavelength Microwave radiometers, 3, 5, 9, and 16mm Radiative cooling only Search for Diffuse Cosmic Radiation at 5-30µ Wavelength High sensitivity Spectrophotometry 5m-30m, liquid helium cooled Experimenters John Mather, *Institution P.I., GISS Rainer Weiss, P.I., MIT Patrick Thaddeus, Dirk Muehlner, Co-I, GISS Rainer Weiss, Co-I, MIT Dirk Muehlner, Co-I, MIT Michael Hauser, Co-I, GSFC Robert Silverberg, Co-I, GSFC Co-I, MIT David Wilkinson, P.I., Princeton Michael Hauser, GSFC Robert Silvery, CO-I, GSFC David Wilkinson, Co-I, Princeton John Mather, Co-I, GISS Instrument $500,000 - Cost 1,000,000 $100,000 - 150,000 $1,000,000 - 1,500,000 $500,000 - 1,000,000

Size EXPLORING THE UNKNOWN 643 30cm diam x 1m long inside cryostat which is 80 cm x 30cm x 60cm on outside of on outside of cryostat 3/4 of circumference, 30 cm thick 20 cm diam x 30cm long inside cryostat cryostat 1m diam x (1/4 of 1.5m long circumference) Mass 20 kg 20 kg 40 kg 20 kg Pointing near vertical, same, but spins about near near vertical, away from sun spinning about near vertical vertical axis away from sun at 1 rpm Telemetry 200 bits/sec 200 bits/sec 200 bits/sec 200 bits/sec Power 2W 5W 15W 2W Required Experiment Lifetime 6 months 1 year 1 year 1 year Document III-23 Document title: Nancy G. Roman, Program Scientist, and C. R. O'Dell, Project Scientist, to Members of the LST Operations and Management Working Group, with attached Minimum Performance Specifications of the LST, February 12, 1975. Source: Space Telescope History Project, National Air and Space Museum, Smithsonian Institution, Washington, D.C. Document III-24 Document title: George B. Field, Director, Center for Astrophysics, Harvard College Observatory, to Dr. James Fletcher, NASA Administrator, February 12, 1976. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C.

644 NASA AND PLANETARY EXPLORATION Document III-25 Document title: James C. Fletcher, NASA Administrator, to James L. Mitchell, Associate Director for Natural Resources, Energy and Science, Office of Management and Budget, April 12, 1976. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Before providing NASA with funds to plan for the Large Space Telescope (LST), the White House, as part of its pressure to reduce the NASA budget in the post-Apollo period, stipulated that the space agency had to find a way to reduce the telescope's cost from the price of $325 mil- lion that NASA was estimating in 1974. NASA thus undertook the task of developing an LST that would satisfy the financial concerns of the White House and Congress as well as the scien- tific objectives of the astronomy community. As even LST “father” Lyman Spitzer realized and advocated, reducing the size of the telescope's 3-meter primary mirror and thus scaling down the entire spacecraft represented one of the most obvious ways to cut the mission's costs. After review- ing the results of studies comparing telescopes with 3-meter, 2.4-meter, and 1.8-meter mirrors, the LST Science Working Group informed NASA that it would be unwilling to support a telescope with a mirror less than 2.4 meters in diameter. In this letter, LST Program Scientist Nancy Roman and LST Project Scientist C. R. O'Dell asked the working group whether they in fact drew the line at 2.4 meters or were willing to negotiate on this number with NASA Headquarters, which was inclined to pursue an even smaller telescope. Astronomers replied that a 2.4-meter mirror was their minimum. Among other factors, the strong opinions of these astronomers ensured that NASA indeed would proceed with a 2.4-meter LST. NASA was unsuccessful in convincing the White House to approve a new start for the LST in the FY 1977 budget, which President Ford transmitted to the Congress in February 1976. This was an outcome that was deeply disappointing to the leaders of the astronomical community, as suggested by the letter from Harvard astrophysicist George Field to NASA Administrator James Fletcher. NASA and the astronomy community redoubled their efforts to get an early start on LST approval and then have the project included in the FY 1978 budget. NASA requested such an approach in Fletcher's April 1976 letter to the Office of Management and Budget. The campaign in support of the LST was successful, and the budget sent to Congress by the outgoing Ford administration in January 1977 contained funds to begin project development. (The FY 1978 budget also contained a new start for another major science project, the Jupiter Orbiter-Probe mis- sion that became Galileo.)

EXPLORING THE UNKNOWN 645 Document III-23 [no page number] TO: Members of the LST Operations and Management Working Group Dear Colleague: February 12, 1975 We appear to be approaching a very pivotal time for LST. As you know, NASA will sub- mit its budget for FY77 (starts 1 October 1976) by May 15 of this year. If LST does not appear as a new start in this budget there is a very real risk of the program foundering. Should this occur, we expect that it might be several years before LST could be restarted and that precursor to LST missions might begin to dominate NASA planning. The issue that will ultimately decide the question is program cost, i.e., if NASA can afford it, we'll have an LST and starting in FY77. As you saw at the December Working Group meeting, the cost figures for all elements except the SSM are by now very well defined and the program is austere. Within a few weeks we will have the SSM contractor's estimates of their costs and the picture will be complete. The program that we are now costing is very significantly reduced from that which we started Phase B with in the summer of 1973. We have de facto reduced the aper- ture to 2.4-m, allowed the angular resolution to degrade, reduced the number of Scientific Instruments, etc. All of us were party to these decisions and we hope that you feel the Program Scientist and Project Scientist have not made these concessions without your full knowledge and consent. We were requested to prepare a document describing the "Minimum Performance Specifications for the LST", which was done in December. (The current version of this is enclosed herewith, slightly revised according to Al Schardt's insistence that the resolution number agreed to at the October meeting was 0.10" and the fact that a theoretically perfect system with a sec- ondary mirror observation of 32% will not give more than about 64% within the first dark ring.) [2] The question for us to address is “Do we defend this as the true minimum LST against efforts to bring the program down in cost by sacrificing performance?" We feel that the costs being identified are well studied and justified for this program and any significant cost savings would be at the expense of performance. Therefore, we are in a position of standing-by [sic] this definition of the minimum LST and running the risk of foundering or renegotiating the cost at a significant cost and performance reduction. Both of us feel that the program has already been so drastically reduced that we are at the point that the line must be drawn and that the agency must either allow us to move ahead with at least this minimum LST, or that we are confronted by an agency money problem and put LST into hold until the future. Although we feel that the derivation of the definition of a minimum LST was done by all of us, we feel that you should have the opportunity to individually and collectively state your opinion at this crucial time, as the risks are quite real. A further complication is the proposal by Al Schardt that we try to reduce program costs by constructing an evolving complexity LST, i.e., one that at initial launch would not

646 NASA AND PLANETARY EXPLORATION meet the minimum performance specifications; but, one that would possess the potential for upgrading later upon successive ground returns to a full LST capability. Although detailed calculations have not been made, it appears that such a plan is plausible and at some reduction in cost to initial launch. The overall cost to eventually reach LST perfor- mance with this plan would certainly be higher than the direct approach. Although Dr. Schardt considers this plan very seriously, he will not support a plan that is not supported by you, the ultimate users and justifiers of LST. It now appears that a decision on FY77 may be made in March, before our next scheduled Working Group meeting. Therefore, we'd like to ask each of you to write us your opinion on “Do we bargain or do we draw the line?” by February 25. Please write to either of us with a copy to the other. We will then set up a telephone confer- ence to summarize the situation. Preferably this conference would be on the after- noon of March 4. Please let us know where you will be on that date, and what are "impossible" times for you. Nancy G. Roman Program Scientist C. R. O'Dell Project Scientist [no page number] [attachment] Revised 27 Dec 1974 Minimum Performance Specifications of the LST The performance specifications imposed by the scientific users of the LST define that set of conditions necessary to have broad scientific support, the ultimate justification for its construction. The present specifications for a minimum LST were prepared by the Project Scientist after consultation with the Program Scientist, the LST Operations and Management Working Group and many other individual astronomers. Individual opinions on specific points vary; however, the following does represent the composite view: 1. LST is a versatile, long life-time observatory; i.e., it must have the capability to accommodate a variety of scientific instruments and vary the complement of instruments with time. 2. The optical image should satisfy the following requirements in the visual and near-vacuum ultraviolet wavelengths: Resolution using the Rayleigh criterion of 0. 08 arc-seconds; A full width half intensity diameter of 0.08 arc-seconds; 80% of the total energy of a stellar image must be contained within a diameter of 0.15 arc- seconds. 3. The overall LST system must work efficiently down to wavelengths permitting the study of the Ly (alpha) line at 1216Å, requiring reaching to about 1150Å. Likewise, it must allow efficient observations at infrared wavelengths longer than those readily accessible from the ground. 4. The system should accommodate at least four scientific instruments. 5. It must be capable of measuring objects appreciably fainter than those accessible from the ground. At the present this means going to about magnitude 27 with a signal to noise ratio of 10 in 4 hours of observing time.

 6. It must be capable of measuring extended sources of surface brightness 23.0 m/[illegible] with a signal to noise ratio of 10 in 15 hours. 7. The LST must have the capability of using Scientific Instrument entrance aper- tures comparable in size to the image. Document III-24 [no page number] Center for Astrophysics 60 Garden Street Cambridge, Massachusetts 02138 February 12, 1976 Dr. James Fletcher, Administrator Code A NASA Headquarters Washington, D.C. 20546 Dear Jim: Harvard College Observatory Smithsonian Astrophysical Observatory I am writing to you in my capacity as a member of the ST Working Group, not as Chairman of PSC, to share my thoughts with you on ST. I hope my comments will be help- ful; they are meant to be. As I am sure you have been, I was surprised by the depth and breadth of the reaction among astronomers to the decision not to have a 77 new start. I felt that the explanation you gave in the authorization hearings was intelligible; certainly the major budget cut thrust upon NASA at the last minute would have made it very difficult to get a new start for ST in 77. Why was the reaction so powerful, then? To me, it simply testifies to the very deep and widespread excitement ST has gen- erated in the astronomical community. I have watched the ST concept grow since I first heard about it from Lyman Spitzer in 1952. The response of the community, at first hesitant, has now reached the point of virtual unanimity among professional astronomers. The reason for this is that the ST, with its diffraction-limited images and its UV and IR capability, promises significant forward steps in virtually all branches of astronomy, and major steps forward in several of them. As a result, astronomers find, when they think about ST, that there are problems they are personally excited about which can be solved by it. Perhaps the ST is unique among space instruments in this respect. ST is not a specialized spacecraft of interest to only a small subdiscipline, but a true observatory with all the broad capabilities one finds at a facility such as Kitt Peak. Such national observatories on the ground are used by large numbers of astronomers for a great diversity of purposes, and for that reason, they enjoy strong

 nationwide support. The same is true of ST, but even more so because of its enormous capabilities. I dwell on the enthusiastic support among astronomers to help you understand the depth of feeling you are now [2] encountering. Astronomers who are normally quite restrained have become passionate because they feel so frustrated. In this con- nection, Jim, I was disappointed that you could not meet with the ST Working Group (although I understood why you could not), because that would have been a good opportunity to defuse their feelings and allay their fears. I feel particularly disap- pointed because strong statements of support like those you made in Williamsburg would have made it very apparent that you mean to start ST in 78. As things are now, there are serious doubts among the senior astronomers as to NASA's true intentions. I think you will candidly admit that even with the best of intentions, it will be very dif- ficult, in view of a possible change of administrations, and the usual problems with the budget, to get a new start in 78. The critical issue, as I see it, Jim (and here I speak completely frankly) is how to transform your statement in Congress into something tangible that will give us something to work with. I am concerned that if this is not done, there will be a really serious loss of morale among the top astronomers who are supporting the project - and I am sure that you are aware that Burbidge, Spitzer, and the others are at the absolute top of their profession. This would be a disaster which we must somehow avoid. If at all possible, Jim, I urge you to commit NASA to major activity for the ST in 77, if possible via a direct authorization by Congress. I want to speak to you candidly about the public attitude toward the ST. Certainly very few of even the educated public are aware of the ST program, and the scientific results that would flow from it. The astronomers, of whom I am one, must take major responsi- bility for not publicizing the concept even better than has been done. But I am absolute- ly sure that with the proper approach, we can tap the wonder of distant and beautiful things that ordinary people feel when given a chance. I would estimate that there are several million people in the U.S. who are fascinated by astronomy, cosmology, deep space, and the universe. Among them are many of our leaders, executives, and publicists. There is a great and enduring fascination with the depths of space and time out of which the earth, life, and finally humanity, arose. If we can show [3] how ST will probe the depths of space and time, we will have opened the door to public support. How can we do this, Jim? An increased program of public education is needed. There are many astronomers who will participate willingly in such work in the year ahead. I am going to try to contact leading publications to offer articles on space astronomy and the ST. Others have offered to do the same. Much can be done through the American Astronomical Society's Task Group on Education in Astronomy, to get materials into newspapers, classroom resource materials, and other educational literature. In all of this, we desperately need the assistance of NASA offices at all levels, includ- ing your own, the program offices, and the public information office. We need contacts with media people, we need guidance, and we need written and visual materials. For some reason, NASA has not been as effective in presenting its space astronomy program as it has its planetary exploration program, and NASA should strive for parity in this area. With proper collaboration between NASA and the scientific community, we can get our mes- sage across. Most of all, Jim, we the astronomers need to meet with you face to face, so that you can allay the fears which cripple effective action, and so that your own interest and excite- ment about ST can be communicated to all. I suggest that you consider addressing a meet- ing of the American Astronomical Society, much as you do the societies associated with the national aerospace effort, for a frank discussion of your hopes for a meaningful space astronomy program. I would be happy to discuss these and any other step we can take toward the ST at any time. Sincerely, [signature] George B. Field Director Document III-25 [stamped] APR 12 1976 Mr. James L. Mitchell Associate Director for Natural Resources, Energy and Science Office of Management and Budget Washington, DC 20503 Dear Jim: Following up John Naugle's recent discussion with Hugh Loweth on the Space Telescope, I would like to summarize our current approach to this project. As I am sure you recognize, a new start for the Space Telescope will be a very high priority item in NASA's FY 1978 budget recommendation. The history of the Space Telescope extends back to studies and scientific discussions in the early 1960s; by 1965, there was a small but growing cadre of astronomers that rec- ognized the unique contributions to many disciplines that could flow from a large tele- scope operating at the diffraction limit above the interference of the atmosphere. With the advent of the shuttle in 1971, it became clear that some of the major prob- lems of maintaining an astronomical facility in space could now be overcome at reason- able costs, and more specific project planning began. The astronomical community eventually settled on a set of technical parameters for a large space telescope: to warrant the considerable investment required, the instrument should be some 10 times more pre- cise than any ground based telescope and should be able to resolve stars of at least the 27th magnitude. These requirements translated into an instrument with a 3-meter aperture operating at or near the diffraction [2] limit. Our early feasibility and design concept studies indi-

650 NASA AND PLANETARY EXPLORATION cated that it was quite possible to build such a telescope, but that its costs would be high- er than either we or the scientific community felt desirable. We then began to examine alternate aperture sizes in relation to probable cost and to technical performance. We found that with an aperture of some 2.4 meters we could meet the scientific requirements and at the same time significantly reduce overall system development complexities and therefore cost. The astronomical community, after some initial concerns that were dissipated by thor- ough engineering analyses, enthusiastically accepted the revised specifications: a 2.4- meter, diffraction-limit aperture and a pointing accuracy of .1 arcsecond. In FY 1975 and 1976, therefore, we funded competitive industry studies for the Space Telescope with all elements designed to come together to support a new start in FY 1977. As it turned out, the Space Telescope was deferred for consideration until the FY 1978 Presidential decision cycle. It appears we had underestimated the commitment to the Space Telescope pro- ject that had grown over the years among scientists, industrial organizations, and members of Congress. We have been inundated with severe criticism from virtually every academic institution associated with astronomy. We have been urged forcefully by the aerospace and optical contractors to do something to alleviate the high costs of their holding together effective engineering teams in order to be able to bid on the telescope project if and when it were authorized and funded. (Here we are dealing with three aerospace firms in competition for the spacecraft and two or more optical houses competing for the telescope assembly; all were geared up to propose in FY 1977 and now are faced with the economics of retaining their technical teams for another year.) The House has chosen to authorize an FY 1977 new start on the Space Telescope at the level of $3 million and our [3] Subcommittee, supported by the urg- ing of the industrial and scientific community, has required us to provide them a plan that would permit early selection of the winning spacecraft and optical contractors (thereby relieving the losers of the considerable financial liability inherent in trying to retain a competitive posture well into next year). Our response to this request from Chairman Fuqua is due early this month. The Senate did not follow the House lead. The Senate bill does not authorize a new start for the telescope in FY 1977, but the report language accompanying the bill is very strong in urging NASA to proceed with the project as “the item of highest priority" in FY 1978 and requesting that NASA sustain the Space Telescope pre-contract activities to assure an orderly and efficient transition into development. The House-Senate conference to accommodate the differences between the two bills is expected to be completed by the Easter recess. We believe we can take certain actions now that would preserve the momentum of the program without committing the Administration and that would permit the House to recede gracefully over the question of the authorization for the Space Telescope. What we propose to do is the following: a. In August of this year, we would issue a formal Request for Proposal (RFP) for the telescope assembly; this RFP would clearly state that: no contract would ensue until and unless there were authorization, appropriation, and apportion- ment actions appropriately taken in the future. The responses to this RFP would

EXPLORING THE UNKNOWN 651 be available in mid-October which would help in the formulation of the President's FY 1978 budget. The NASA source evaluation process would proceed during the winter and be completed in the March-April period of 1977 -- well after the decisions on the President's [4] budget and even after the completion of the authorization and appropriation hearings. Depending on the situation at that time, we could then terminate the process (if the project were not approved) or proceed with detailed negotiations aimed at a contract effective on October 1, 1977. b. We would follow essentially the same pattern with the spacecraft RFP, except it would be released in October of 1976, responded to in December of 1976, and the responses evaluated by May or June of 1977. C. We would solicit Principal Investigator responses for the Space Telescope's scien- tific instrumentation beginning around September of this year and extending well into 1977 before any decision would be made. We feel that this limited action, not committing the Administration in advance of the normal budget process, will place us in a sound position to proceed with the pro- ject if it is approved during the coming cycle. Conversely, we feel that to take no steps until mid-1977 would result in serious program discontinuities and even some inequities-: — Some of the contractors have indicated that they might be unable to maintain their teams and competitive postures until mid-1977 and would therefore be unable to bid. All the contractors have indicated a strong desire for an early selection process even in the absence of funding. All the contractors have stated that their technical positions would have seriously eroded by mid-1977, leading to weaker technical proposals and greater cost uncertainties (some have said they would require an additional preliminary design phase, extending the program and increasing its costs). [5] The Congressional supporters of the Space Telescope might be moved to force unnecessary and undesirable confrontations with NASA and the Administration on the question of responsiveness to their guidance. - The scientific supporters of the Space Telescope would continue to exert what pressures they could for an overt action by the Congress and the Administration, perhaps thereby reducing some of the positive impact of the President's recent science and technology message. In summary, we feel that the most prudent course to take is to inform the interested communities on a low-key basis that we will proceed with an early selection process begin- ning in late summer. We believe that this approach will not commit the Administration in advance of the normal budget process, that it will retain the necessary flexibility on the part of the Government to adjust its plans to fit future situations as they become real, and that it will capitalize on current support for the Administration's posture on science and technology.

652 Sincerely, [Original signed by] James C. Fletcher Administrator bcc: A/Dr. Fletcher AD/Dr. Low AA/Dr. Naugle ADA/Gen. Crow B/Mr. Lilly X/Mr. Williamson SD/Dr. Calio AEM-3/Ms. LeCompte NASA AND PLANETARY EXPLORATION Document III-26 Document title: Smithsonian Institution Astrophysical Observatory, “Proposal to National Aeronautics and Space Administration for the Study of the 1.2 Meter X-ray Telescope National Space Observatory,” April 1976. Source: Harvey Tannenbaum, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, reprinted with permission. By the mid-1970s, NASA had taken a strong interest in high-energy astronomy, as evidenced by the launch of Uhuru and the development of the High Energy Astronomy Observatories. Encouraged by NASA's commitment to studying high-energy wavelengths, astronomers at the Smithsonian Astrophysical Observatory presented to NASA in 1976 an unsolicited proposal for the development of a major space-based x-ray observatory. The proposed spacecraft would enable astronomers to see farther than ever before possible into a universe of exploding stars, colliding galaxies, and enigmatic black holes-phenomena evident only by the x-rays they emit. Embracing the idea of this mission, which became known as the Advanced X-ray Astrophysics Facility, NASA began conceptual studies and assembled a working group to define scientific objectives for the mission in 1977. The satellite was finally launched, and named Chandra, in 1995.

 ers, in generating new capabilities for the ST. Unless it is thus involved in advancing the state of the art, it will be difficult for the Institute to recruit and keep a professional staff of the requisite quality. 11. By means of an extended staff and decentralization of some of its functions, the Institute should ensure broad, intimate, and responsible involvement of the astronomical community. 12. The Institute must be responsible for the scientific direction of the ST and should be involved in the provision of modified and second-generation instrumentation. 13. In order to make the best use of scarce and valuable observing time, the astro- nomical community should be involved through the Institute in the evaluation of experi- ments and the allocation of time on the telescope. 14. We suggest that initially a portion of the observing time on the ST be allocated to the Institute for two reasons: to assist in recruiting a Director and staff of the highest qual- ity, and to permit the staff to become acquainted rapidly with the possibilities and limita- tions of the ST and its associated systems. 15. The Institute does not need to duplicate the full image-correction capability at the Goddard Space Flight Center (GSFC), which requires a very large computer, nor need it have access to a high-capacity land line. 16. For scientific interpretation of data, the Institute needs moderate scale computa- tional facilities which can be linked to remote minicomputers at perhaps ten centers in the country. 17. The Institute should coordinate the development of software that can be used at remote sites to reduce and interpret data derived from the ST. 18. We recommend that arrangements be made for close liaison with appropriate NASA organizations. In particular, we recommend that the principal responsibility for liai- son with the NASA Project Manager rest with a senior staff member of the Institute and that representatives of the Institute be resident in the Mission Operations Center at GSFC. 19. We recommend that arrangements be made for international participation in the Institute, including its policy-making bodies. 20. It would be advantageous to the Institute if its basic funding could be [3] supple- mented with private funds to provide discretionary resources. This might be achieved through an initiation fee and annual dues from members of the consortium. However, to provide long-term stability for the Institute, we believe it important eventually to raise an endowment from foundations and individuals. 21. We recommend that the Institute be favorably located for recruiting a high-caliber staff. We believe this requires proximity to a first-rate scientific center, availability of good schools and housing, and a stimulating environment. 22. We recommend that the Institute be located so that land, buildings, shops, and engineering facilities are available on a scale that will meet the initial needs of the Institute. 23. We recommend that the Institute be located where it has easy access to a major international airport. 24. We have not found any compelling data-handling, managerial, or cost reasons for locating the Institute at an existing NASA center. 25. Special arrangements should be developed to ensure ready access by the Institute to large, ground-based telescopes that may be needed to support the operation of the Space Telescope. 26. Although the model of an institute we have proposed may be applicable to other space-based astronomy projects, we have not addressed the question of their possible inclusion in the STScI. 27. The selection of a consortium and the search for a site should be initiated in the near future. Document III-28 Document title: “Announcement of Opportunity for Space Telescope,” March 1977. Source: Space Telescope History Project, National Air and Space Museum, Smithsonian Institution, Washington, D.C. With the Space Telescope approved as a new start by the White House, NASA in early 1977 felt free to announce to the scientific community the opportunities for its use. This initial Announcement of Opportunity spelled out the conditions for scientists' access to the facility. [1] [Stamped "18 Mar 1977"] AO No. OSS-1-77 ANNOUNCEMENT OF OPPORTUNITY FOR SPACE TELESCOPE I. DESCRIPTION OF OPPORTUNITY The National Aeronautics and Space Administration (NASA) announces the solicita- tion of proposals for scientific investigations and related participation in the Space Telescope (ST). This mission is under consideration for launch by the Space Shuttle dur- ing the fourth quarter of Calendar Year 1983. While the implementation of the ST pro- gram has not yet been approved by Congress, an early selection of scientific participants will permit a prompt start on scientific planning and related hardware definition, if and when such approval is received. This solicitation does not constitute an obligation on the part of the U.S. Government to carry the proposed effort to completion. The ST Program is conceived as a long-term program in space astronomy that will pro- vide mankind with an astronomical capability achievable by any current or foreseeable ground-based telescope. A high-resolution 2.4 meter telescope will be placed in a circular Earth orbit at an altitude of approximately 500 km with an inclination of 28.8 to the equator. The telescope will be an F/24 Ritchey-Chretien design (34% central obscuration

EXPLORING THE UNKNOWN 665 diameter ratio) with a focal plane data field 0.30 m in diameter. It will provide point- source images with 70% energy within a diameter of £ 0.2 arc seconds at 633 nm and will have useful sensitivity over the wavelength range 120 nm to 1 mm. Up to five Scientific Instruments (SI's) will be accommodated at the focal plane. [2] The ST will differ from existing automated satellites in that it will be designed to per- mit on-orbit maintenance and repair by a space-suited astronaut and be retrievable by the Space Shuttle for return to Earth for refurbishment and subsequent relaunch. A feature of the design will be the provision for replacement of any of the focal-plane SI's at the time of on-orbit visits or during ground refurbishment. This will allow updating of the instru- mentation and the use of the ST to fulfill a broad range of scientific requirements over its lifetime, which is expected to exceed a decade. The on-orbit visits and/or refurbishments are nominally scheduled for 30-month intervals; however, the exact timing will depend on the operating efficiency and scientific program of the ST. The overall ST Project is being managed by Marshall Space Flight Center (MSFC). Goddard Space Flight Center (GSFC) is responsible for managing the development of the SI's and for post-launch operation of the observatory. This Announcement of Opportunity (AO) is a solicitation of proposals for the scien- tific investigations and the definition and development of focal-plane SI's required to carry out the investigations and for individual “Observatory Scientists" who will be select- ed to perform scientific investigations using the initial complement of focal-plane SI's and to assist the ST Project in working out scientific mission parameters, as delineated later in this AO. One of the initial focal-plane SI's, a Faint Object Camera (FOC), will be provid- ed by the European Space Agency (ESA), subject to satisfactory negotiation of a formal agreement between NASA and ESA. Scientists selected through this AO and who participate substantially in the develop- ment of the ST and its initial focal-plane SI's will be allocated observing time in the early months of operation. Specifically, proposals are now solicited from: A. Investigation Definition Teams (IDT's), each consisting of a Principal Investigation (PI) and appropriate Co-Investigators (Co-I's) proposing a scientific investigation and the definition and development of focal-plane instrumentation required to carry out that sci- entific investigation; [3] B. Individual investigators who desire consideration as a Co-I on an IDT (including U.S. representation on the ESA FOC team); and, C. Individual investigators who desire to participate as Observatory Scientists. For a more detailed description of all categories of participation, see Section V.A. [not included] The PI's, Observatory Scientists, and appropriate NASA and ESA scientists will con- stitute an ST Science Working Group, chaired by the NASA Project Scientist. This Working Group will assist the ST Project in working out scientific mission parameters. II. MISSION OBJECTIVES Scientific Objectives The scientific objectives of the ST are to determine: A. The constitution, physical characteristics, and dynamics of celestial entities;

 B. The nature of processes which occur in the extreme physical conditions existing in and between astronomical objects; C. The history and evolution of the universe; and, D. Whether the laws of nature are universal in the space-time continuum. The ST will increase the sensitivity and resolving power and extend the spectral range of astronomical observations decisively beyond those achievable from ground-based observatories. While it is likely that the ST will reveal unimagined phenomena and, hence, will open new areas of scientific inquiry, the following are examples of the type of specif- ic scientific objectives, within the broader objectives above, which have been suggested. (These specific objectives are not intended to limit the scope of scientific programs which may be proposed by respondents to this AO. However, to be considered for selection, proposals must be within the scope of the scientific objectives of the ST, as stated above.) [4] • • • • • • • [5] • • . • Precise determination of distances to galaxies out to expansion velocities $\sim 10^{1}$km s$^{1}$ and calibration of distance criteria applicable at cosmologically significant dis- tances Determination of the rate of the deceleration of the Hubble expansion of the uni- verse, its uniformity in different directions, and possibly its constancy with time Testing of the basic reality of the universal expansion by determination of the sur- face brightness versus red shift relation for distant galaxies Establishment of the history of star formation and nuclear processing of matter as a function of position in nearby galaxies and determination of the variations from galaxy to galaxy Determination of the nature of stellar populations in the early stages of galactic evolution, based on “lookback” observations of distant galaxies Estimation of the He⁄H ratio in quasars by observation of red-shifted He I and He II resonance lines Search for multiple-red-shift absorption line groups in the ultraviolet spectra of low-red-shift quasars Intercomparison of total spectra of high-red-shift quasars, low-red-shift quasars, and active galactic nuclei Resolution of densely-packed nuclei of globular star clusters in search of massive black holes Identification and flux measurement in ultraviolet and optical wavelengths of faint x-ray sources and radio pulsars Resolution of the complex internal structure of Herbig-Haro objects to investi- gate their possible links to star formation High spatial resolution, infrared observations of proto-stars Direct imaging and astrometric search for planetary companions of nearby stars Determination of bolometric luminosities of faint, hot stars for studies of stellar evolution Determination of composition, temperature, density, and ionization structure of the gas in the galactic halo, in high-velocity clouds, and in the intergalactic medium Precise mapping of the 100 mm flux sources in compact H II regions

 Determination of composition of clouds in the atmospheres of Jupiter, Saturn, Uranus, and Neptune Surface mapping of the Galilean satellites of Jupiter and of asteroids Synoptic mapping of atmospheric features on Venus, Jupiter, Saturn, and Uranus Intensity measurements of atomic and molecular ultraviolet emission lines impor- tant to understanding the chemistry of comets III. SPECIFIC REQUIREMENTS AND CONSTRAINTS ON INVESTIGATION DEFINI- TION TEAM (IDT) PROPOSALS The ST and its SI's will be designed and developed within the framework of a tightly cost-controlled program, leading to the proposed launch in the fourth quarter of 1983. The SI's will be delivered to GSFC 28 months prior to launch for NASA acceptance test- ing and verification. The number and amount of associated development of instruments required for investigations selected for the first mission will be limited by the total fund- ing available in the program budget. It is imperative that proposers establish a credible low-cost approach and schedule for the development of flight-quality instruments and associated hardware. [6] Initial IDT selections will be tentative. Following tentative selection, each PI will be fund- ed to carry out a preliminary design study, including breadboarding or other activities nec- essary to verify the detailed approach and costs for the final instrument development phase. At the end of this initial activity, the PI (if responsible for instrument development) will sub- mit an updated implementation plan and schedule for the instrument development. NASA will then reevaluate the scientific, technological, and cost aspects of each instrument. Based on this reevaluation, the NASA Associate Administrator for Space Science will confirm the participation as originally determined, direct modifications to meet Project schedule and funding limitations, or terminate the proposed participation. At that time, firm commitments to performance specifications, costs, schedule, and scope will be established for each instru- ment development to be completed. Contracts for participation in the operations phase of the Project and for the timely deposit of the resulting data in the National Space Science Data Center will be negotiated later. Preliminary studies have been carried out for the types of instruments listed below. Final reports on these studies, as well as on separate studies of various detectors appro- priate for use in the instruments, are available by use of the attached order form (Attachment M) [not included]. A. Ultraviolet Spectrographs 1. Faint Object Spectrograph (FOS) 2. High Resolution Spectrograph (HRS) 3. Combined FOS-HRS B. High Resolution Cameras 1. Wide Field Camera (WFC) 2. Faint Object Camera (FOC) (to be provided by ESA) 3. Planetary Camera (PC) C. Photometers 1. Infrared Photometer (IRP) 2. High-Speed Photometer (HSP)

 D. Guidance System (Astrometry) [7] NASA has determined that, for reasons of cost-effectiveness, astrometry will be carried out with the spacecraft guidance system and no separate SI will be developed for astrom- etry. NASA will, however, select a scientific investigation in this area involving a PI and pos- sibly several team members. Also, NASA (with the advice of the astronomical community) has designated the WFC and the FOS as particularly important. If qualified proposals for investigations involving these instruments are received, a WFC and an FOS will be selected for inclusion in the ini- tial instrument complement. Qualified proposals are those for investigations which are considered to be well conceived, scientifically and technically sound, and pertinent to the goals and objectives of the ST Program. In addition, they must be offered by a competent investigator from an institution capable of supplying the necessary technical and man- agement capabilities to ensure that flight hardware or other support can be delivered on time and within budget and that data can be properly reduced, analyzed, interpreted, and published in a reasonable time. Finally, qualified proposals are those recommended, with high priority, for tentative selection. Proposals may be submitted for investigations responsive to the stated objectives of this AO and entailing the design, development, and scientific application of any suitable instrument (excepting an FOC or astrometry instrument), whether or not it was previ- ously studied. The proposer must establish the scientific merit, technical feasibility, inter- face compatibility, consistency of the effort with the proposed budget and schedule, and the existence of wide interest within the scientific community. A working description of the FOC to be provided by ESA is contained in the attached summary of scientific performance goals (Attachment H) [not included]. IV. ALLOCATION OF OBSERVING TIME Those scientists selected for participation in the ST Program as a result of this solici- tation will be involved in the development of the ST and its initial complement of instru- ments. After launch, they will be involved in the on-orbit checkout expected to last about one month, after which the ST will be declared operational. [8] As has been the custom for ground-based telescopes, observing time will be assigned pri- marily on the basis of the scientific merit of the competitive observational proposals. During the first 30 months after the ST is declared operational, a portion of the observing time will be allocated to the IDT's, the Astronomy Team, and the Observatory Scientists selected as a result of this solicitation. The remainder of the observing time until the first on-orbit main- tenance will be available for the general ST Observer Program which will be the subject of subsequent AO's, the first of which will be issued about nine months before the initial launch. Scientists selected now will be free to compete for this additional time. The monthly percentages of the total observing time, which will be allocated to the IDT's, the Astronomy Team, and Observatory Scientists, are as follows: Period Months 1-2 (after checkout period) Months 3-8 Months 9-20 Months 21-30 % Allocated 100% 50% 25% 10%

 In dividing the above time allocations among the various participants, the Observatory Scientists, as a group, will be treated in the same manner as a single IDT or Astronomy team. The U.S. member(s) chosen for the ESA FOC Team will be allo- cated time comparable to that allocated to Co-I's on U.S. IDT's. While the IDT's will have priority on the use of their own instrument during this allocated time, they may negotiate observing time on other SI's which may be required to complement their own investigations. NASA is considering the establishment of an ST science operations facility which would manage the scientific use of the ST during its operational life. Observing time for all observers, including those selected by this and subsequent AO's, would be scheduled by this operations facility. PI's will have an ongoing responsibility during the period after post-launch checkout to assist in the operation, calibration... [9] V. EVALUATION AND SELECTION PROCESS A. Categories of Participation 1. Investigation Definition Teams (IDT's) Proposals are solicited for scientific investigations and for definition and development of scientific focal-plane instruments for the ST required to carry out the investigations. In addition to a complete description of the scientific investigation, proposals should cover the development of the entire required instrument, including detectors. The proposing Team should consist of a PI and the Co-I's necessary to complete the proposed investiga- tion. NASA may elect to delete members of the proposed Team and/or augment the membership of Teams with selected scientists who have proposed individually or as part of other Teams. 2. Individual Investigators Proposals are invited from individual scientists not allied with a proposing Team who wish to propose scientific investigations which may impact the design of a partic- ular instrument or who are interested in the astrometric use of the fine guidance sys- tem. NASA may select such individual scientists as PI's or as additional Co-I's on IDT's. The U.S. scientists interested in performing investigations with the FOC and partici- pating on the ESA FOC Team should also propose as individuals. It should be noted that the one or more U.S. members of the FOC Team will need to travel extensively. Individual instrumentalists, e.g., detector specialists, are encouraged to affiliate with more than one IDT proposal. Separate detector proposals should not be submitted to NASA in response to this AO. [10] 3. Observatory Scientists Proposals are invited from scientists wishing to serve in one of the following capacities: Telescope Scientists, Interdisciplinary Scientists, and Data and Operations Team Leader. Telescope Scientists will carry out scientific investigations and will assist the ST Project to assure that the spacecraft is compatible with scientific requirements. In addition to proposing a qualified scientific investigation for the ST, individuals proposing as Telescope Scientists should have a broad knowledge of imaging optical systems, with a working knowledge of the relation of optical and thermal mechanical systems and their effects on the performance of the observatory.

 Interdisciplinary Scientists are generalists or theoreticians who, in addition to car- rying out scientific investigations using the ST, will serve the Project by maintaining a broad and critical scientific overview of the ST development. Proposers as Interdisciplinary Scientists should not only propose qualified specific scientific inves- tigations using the ST but should also have a thorough knowledge of the forefront problems of modern astronomy and astrophysics and a clear interest in applying the capabilities of the ST to those problems. Moreover, these scientists must be able to relate the potential attainment of general scientific goals to specific characteristics of the ST and SI performance. The Data and Operations Teams Leader will carry out scientific investigations and will assist the Project to assure that the SI Control and Data Handling System is con- sistent with scientific requirements. He will head a Team consisting of a representative from each of the IDT's, which will assist in developing the detailed requirements for the SI Control and Data Handling System and in providing integrate SI operations and data management requirements. Proposers for the Data and Operations Team Leader, in addition to proposing a qualified scientific investigation for the ST, should have a good understanding of instrument and control systems, flight operation, and ground data handling systems. Document III-29 Document title: "Memorandum of Understanding Between The European Space Agency and The United States National Aeronautics and Space Administration," October 7, 1977. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. In order to gain Congressional approval of the Space Telescope, NASA had agreed that it would seek significant international participation in the effort. In practice, given the status of other space pro- grams in the 1970s, this meant inviting European participation in the project. Europe agreed to sup- ply a major scientific instrument, the Faint Object Camera, and solar panels for the telescope in return for a guarantee of fifteen percent of the observing time. While NASA agreed to this arrangement, it was controversial among some members of the U.S. scientific community, both because they could not compete to supply the scientific instrument and the arrangement might decrease the observing time available to them.

[no pagination] EXPLORING THE UNKNOWN 671 MEMORANDUM OF UNDERSTANDING BETWEEN THE EUROPEAN SPACE AGENCY AND THE UNITED STATES NATIONAL AERONAUTICS AND SPACE ADMINISTRATION ARTICLE 1 Purpose The European Space Agency (ESA) and the United States National Aeronautics and Space Administration (NASA), desiring to extend the fruitful cooperation developed in previous space projects, agree that ESA will participate in the NASA 2.4 Meter Space Telescope (ST) Project, as described below. ARTICLE 2 Mission The mission of the ST Project is to provide a space observatory for use by the international astronomy community to extend the sensitivity, resolving power and spectral range of astronomical observations decisively beyond those achievable from earth observatories. ARTICLE 3 Participation 1. To carry out this project, NASA plans to launch the ST by means of the Space Shuttle in1983/1984 and to operate it for a period of 10 to 15 years. ESA agrees to assist in the provision of scientific instruments and subsystems for the ST, in the operation of the ST and related facilities, in the in-orbit maintenance, major refurbishments and reflights, at anticipated intervals of two or three years, and to arrange for participation of ESA-spon- sored astronomers in the observation programs. 2. ESA will carry out its participation in accordance with the plans, specifications and schedules contained in the NASA/ESA ST Project Plan annexed to this Memorandum of Understanding. [not included] This plan may be subject to change as defined in Article 7 (d) below. ARTICLE 4 ESA responsibilities To implement the cooperation in this project ESA will: (a) Provide the Faint Object Camera (FOC), a scientific instrument of high sensitivi- ty for high resolution imagery in the ultraviolet, visual, and near infrared portions of the spectrum. The performance specification for this instrument is included in the NASA/ESA ST Project Plan annexed to this Memorandum of Understanding. With respect to the provision of the FOC, ESA will: (i) design, fabricate, test, calibrate and deliver for integration into the ST the FOC, comprising the camera optics and an Imaging Photon Counting System (IPCS). The FOC models and associated hardware together with the sched- ule for their delivery are defined in the NASA/ESA ST Project Plan; (ii) provide personnel and equipment to support NASA activities relating to test- ing, integration of the FOC with the ST, and launch site operations, as defined in the NASA/ESA ST Project Plan; (iii) set up an ESA Instrument Science Team (IST) to ensure the scientific integri- ty of the definition and design of the FOC, and its compatibility with the tele- scope, and to provide scientific advice for the ESA project management, which will manage FOC development. It is agreed that at least one NASA- appointed scientist will be a member of the IST; (iv) provide participation in NASA reviews in accordance with Article 8 (b) (iii) below; (v) develop the ground and flight software packages uniquely required for the FOC, as defined in the NASA/ESA ST Project Plan; (vi) provide a team of two to four instrument and data scientists to support the operations of the FOC after launch, as mutually agreed; and, (vii) refurbish the FOC for reflight, and provide necessary support for mainte- nance or modification of the FOC in-orbit, when mutually agreed. In the event NASA wishes to refurbish or modify the FOC and ESA does not desire to do either, ESA will provide the available documentation and other support as agreed between the Project Managers. (b) Provide the ST Solar Array. In this respect, ESA will: (i) design, fabricate, test and deliver to the NASA Support Systems Module (SSM) contractor for integration with the Space Telescope a complete solar array and associated hardware, the performance specification, interface requirements, number of models and hardware parts and their delivery schedule being defined in the NASA/ESA ST Project Plan; (ii) provide personnel and equipment to support the handling and testing of the solar arrays while they an not attached to the ST spacecraft, as defined in the NASA/ESA Project Plan; (iii) provide appropriate representation in NASA reviews in accordance with Article 8 (b) (iii) below; (iv) maintain continuing engineering liaison with NASA ST project elements which interface with the ESA solar array; (v) provide personnel and equipment to support NASA activities relating to test- ing, integration of the solar array with the ST, and launch site operations, as defined in the NASA/ESA ST Project Plan; and (vi) refurbish, repair, and/or replace the solar array and provide support to NASA for its maintenance or modification in-orbit, as mutually agreed and reflect- ed in the NASA/ESA ST Project Plan.

EXPLORING THE UNKNOWN 673 (c) Participate in the activities of the science operations facility as described in Article 7 (g) below. In this respect ESA will, in particular: (i) provide a team of approximately six persons to support one shift of the sci- entific planning and operation tasks of the science operations facility; (ii) provide a team of approximately seven persons to support the ST scientific data reduction shift of the science operations facility; (iii) provide membership to this facility, as mutually agreed, in order to partici- pate in the definition and implementation of the ST science activities; and (iv) provide a representative to NASA to serve as a focal point for NASA/ESA con- sultations regarding the establishment and operation of the science opera- tions facility; it being understood that the members of the ESA teams mentioned in (i) and (ii) above will be considered functionally as members of the science operations facility. ARTICLE 5 NASA responsibilities To carry out the cooperation in this project, NASA will: (a) Design, fabricate, test, integrate and prepare for launching the complete ST assembly. (b) Define jointly with ESA the solar array interfaces, design requirements, and test and handling specification, and provide this information to ESA in accordance with the schedule defined in the NASA/ESA ST Project Plan. (c) Test the solar array when it is integrated on the ST and supply ESA with relevant engineering data. NASA is responsible for handling of the solar array after its acceptance at the integration site. (d) Provide appropriate representation at ESA reviews in accordance with Article 8 (b) (iv) below. (e) Provide and transport to the launch site all necessary ST ground support equip- ment, including items delivered by ESA to the test and integration sites to support the FOC and the solar array. (f) Transport to the launch site the flight qualified ST and perform necessary tests and checkout prior to launch. (g) Provide initial launching of the ST on a Space Shuttle, release the ST into the des- ignated orbit, and conduct, with ESA participation, checkout of the ST as required for a period of approximately 30 days following launch. (h) Provide all tracking and data acquisition services during the lifetime of the project. (i) Exercise all in-orbit control functions. To accomplish this, NASA will organize, equip, staff, train and operate an operations center. (j) Include the FOC in the payload of the first flight of the ST and operate it in accor- dance with the provisions of Article 6 below. (k) Establish a science operations facility to conduct scientific operations as outlined in Article 7 (g) below.

674 NASA AND PLANETARY EXPLORATION (1) Provide in-orbit maintenance, and retrieve and relaunch the ST when necessary according to operations plans, and conduct refurbishment and in-orbit modification operations assisted by ESA as provided in Articles 4 (a) (vii) and 4 (b) (vi) above. ARTICLE 6 Flight arid Operation of the ESA-supplied FOC I. The following principles shall apply to the flights of the ESA-supplied FOC: (a) Assuming normal functioning, it will be operated by NASA for a nominal initial period of thirty months. (b) Following this period, it will be flown as long as it is decided to be a component of the scientifically optimum payload. (c) Following the initial or subsequent operating periods, both parties may never- theless agree that NASA will continue to fly it in modified form, in application of Article 4 (a) (vii), or replace it for a given period by another scientific instrument. (d) If the FOC fails to meat the minimum scientific requirements laid down in the per- formance specification as defined in the NASA/ESA ST Project Plan, or if the delivery by ESA would substantially delay the first flight, NASA may decide, after consultation with ESA, to launch the ST without the FOC. In this event, provided that, at the rele- vant time, the FOC does meet the minimum scientific requirements referred to above, NASA will take its availability into account when funding the development of ST instru- ments for subsequent flights and accept it as a candidate instrument for those flights. II. Decisions concerning the implementation of the provision of the foregoing para- graph shall be made by the NASA Associate Administrator for Space Science and the appropriate Director at ESA Headquarters, subject to the application of the provisions of Article 18 of this Memorandum of Understanding. ARTICLE 7 Management and Organization Unless otherwise provided in this Memorandum of Understanding, the management arrangements are understood by NASA and ESA to be as follows: (a) NASA will establish a ST Project Office to provide for project planning and man- agement with the following responsibilities: (i) Overall responsibility for the design, fabrication, test, integration, launch, in- orbit verification, and operation of the ST; (ii) flight performance evaluation, and planning for and carrying out in-orbit maintenance and modification; and (iii) planning and carrying out ST refurbishments. (b) The Project Office will be headed by a NASA Project Manager. To carry out the ST Project, the Project Manager will be supported by a full-time staff of managers and engineers. Full responsibility for management of the ST Project resides with the NASA Project Manager. The Project Office provides the principal means for carrying out these management responsibilities.

 (c) ESA will: (i) Designate an ESA Project Manager for overall coordination, planning and execution of the ESA tasks described in this Memorandum of Understanding, and will assign appropriate representation to the ST Project Office, as mutu- ally agreed; and (ii) Appoint an ESA Project Scientist. (d) Management and technical decisions which have a bearing on the execution of ESA tasks as described under this Memorandum of Understanding or affect the contents of the annexed NASA/ESA ST Project Plan, and items with respect to which mutual agreement is necessary in accordance with provisions of this Memorandum, shall be taken in common by the NASA and the ESA Project Managers. If they are unable to come to an agreement on a particular issue, it shall be referred to the NASA Associate Administrator for Space Science for resolution in consultation with the appropriate Director at ESA Headquarters, subject to the application of the provisions of Article 18 of this Memorandum of Understanding. (e) NASA will establish a Space Telescope Science Working Group (ST-SWG) which will be the principal mechanism for scientific input to the Project Office during the development of the ST. The ST-SWG will be chaired by the ST Project Scientist des- ignated by NASA. The ESA membership on the ST-SWG will consist of the ESA Project Scientist referred to in paragraph (c) of this Article and of the Chairman of the ESA IST referred to in Article 4 (a) (iii), who will be assisted by such members of his team as he desires to be present for specific ST-SWG meetings. (f) NASA will establish a mission operations center, as defined to the NASA/ESA Project Plan to: (i) Carry out mission operations planning; (ii) execute ST command and control; (iii) acquire data on and evaluate ST engineering performance; (iv) report ST anomalies; (v) reduce ST engineering data; and (vi) acquire and process ST scientific data. (g) NASA will establish a science operations facility to carry out scientific manage- ment of the observatory in orbit. Operational support of the investigators by this facility will include, but is not limited to: (i) Planning long-term scientific operations; (ii) scheduling daily scientific observations; (iii) conducting real time scientific observations; and (iv) performing ST scientific data management, including making available ST scientific data to investigators in a form suitable for analysis. ESA will be represented and participate in this facility in accordance with the provisions of Article 4 (c). ESA participation in the daily activities of the science operations facility will include, but will not be limited to the provision of the support provided under Article 4 (a) (vi) and 4 (c) above.

 ARTICLE 8 Technical interfaces The management of the technical interfaces on the ST will be carried out with a min- imum of documentation and formal reviews. It is understood between ESA and NASA that the following principles and procedures will apply: (a) General Responsibilities for Technical Interfaces (i) The NASA Project Manager, in accordance with Article 7 (b) above, is respon- sible for the management of the interfaces, including documentation, gen- eral control of the use of such documentation, and the conduct of technical reviews on all systems for which NASA is responsible: (ii) The ESA Project Manager is responsible to work to such requirements and interfaces as he and the NASA Project Manager have mutually agreed to, and for the conduct of technical reviews to insure that all systems and hardware for which ESA is responsible comply with ST interface requirements. (b) Specific Responsibilities and Procedures (i) The NASA Project Manager will review and mutually agree with the ESA Project Manager, as to which standards and specifications will be considered to constitute the requirements for control purposes in the ST Project. The agreed standards and specifications, if any, will be referenced as part of the NASA/ESA ST Project Plan. (ii) ESA will supply data to NASA for the generation of appropriate Interface Requirements Documentation (IRDs) Interface Control Drawings (ICDs) and Contract End Item (CEI) Specifications Part I for the Solar array and the FOC. The CEI Specifications Part II for the Solar array and the FOC will be generated by ESA. The Project Managers will mutually agree on these documents, and the NASA Project Manager will approve them in accor- dance with a schedule in the NASA/ESA ST Project Plan. Subsequent mod- ifications to either the IRDS, the ICDs, or the CEI Specification will be approved by appropriate change control procedures identified in the NASA/ESA ST Project Plan. Should such modifications seem unacceptable to either Project Manager for financial or schedule reasons, the provisions of Article IS will apply. (iii) NASA will make final determination of the overall readiness of the ST for launching. This determination will be based on periodic reviews chaired by NASA to address the concept, design, and readiness for flight of the ST. ESA will have appropriate representation at selected reviews and will furnish engi- neering data as agreed by the Project Managers. (iv) Determination of the readiness for integration of the solar array and the FOC will be based on periodic reviews, chaired by ESA, of the concept, design and readiness for flight of the hardware. NASA will have appropriate representa- tion at these reviews as agreed between the Project Managers and will furnish engineering data as agreed by the Project managers. Final determination of the readiness for integration of the solar array and the FOC will be the responsibility of the NASA Project Manager, based on recommendations from the ESA Project Manager and review committees. (v) NASA and ESA shall have full access to, and the right to use and disclose, non- proprietary data necessary to discharge their respective responsibilities under this Memorandum of Understanding. In principle, there will be no transfer of documents bearing proprietary or other restrictive markings. To achieve this, optimal use will be made of mathematical models, mock ups and simu- lators, as appropriate to assure hardware interface and operations compati- bility. Should either party consider that the above limitation prevents it from carrying out a particular responsibility under this Memorandum of Understanding, the Project Managers will determine a mutually agreeable solution on a case-by-case basis. In the event that the solution must involve the transfer of proprietary data, the furnishing party, with the consent of the pro- prietor, shall furnish the data and shall merit them with a notice limiting the use and disclosure of the information for ST Project purposes only, and the receiving party will use its best efforts to comply with such limitations. (vi) Detailed arrangements for working level technical interfaces, including NASA and ESA contractors, are defined in the NASA/ESA ST Project Plan. ARTICLE 9 Apportionment of Observing Time 1. The term "observing time" as used in this Article is understood to mean that time dur- ing which the ST instruments are in operation, less idle time and time necessary for calibration, testing and maintenance. 2. NASA and ESA agree that ST observing time will be made available to investigators from the international community of astronomers on the basis of the scientific merit of proposals made. 3. Subject to the application of this principle, and in consideration of ESA's participa- tion as defined in this Memorandum of Understanding, ESA will obtain, for use by ESA-sponsored astronomers, a portion of the observing time on the total complement of scientific instruments of the ST. It is expected and intended that this portion will be not less than 15 % of the observing time on the average over the lifetime of the ST Project. ARTICLE 10 Selection of Observing Programs 1. All proposals for observing programs from astronomers in ESA member States will be submitted in accordance with ESA procedures to the ST Proposal Review Committee (STPRC), which will be the primary body for the review and evaluation of all propos- als for observing programs to be carried out on the ST. 2. The STPRC will have an appropriate European membership (minimum of two), the number to be agreed between ESA and NASA Headquarters. It will make recommen- dations for observing programs to the NASA Associate Administrator for Space

 Science, who, after consultation with ESA as necessary, will make a final determina- tion of the observing programs. 3. Should ESA consider that the observing programs so determined are inconsistent with the provisions of Article 9, or should there be a major alteration in the ESA par- ticipation in the ST Project, either party may request a joint review of the evaluation and selection process. ARTICLE 11 Deposit Accounts Should ESA desire that NASA procure goods and services on ESA's behalf to assist ESA in carrying out an ESA responsibility under this Memorandum of Understanding, NASA is prepared to consider such requests on a case-by-case basis under the provisions of a Deposit Account Agreement to be negotiated separately. Similar requests from NASA will be treated by ESA accordingly. ARTICLE 12 Funding Arrangements Each Agency will arrange to meet the cost of discharging its responsibilities, including travel and subsistence for its own authorized personnel and transportation charges on all equipment and flight hardware for which it is responsible. Other than deposit account transactions referred to in Article 11, there will be no exchange of funds between ESA and NASA. ARTICLE 13 Custom and Visas ESA and NASA will use their best efforts to arrange free customs clearance for equipment required in the ST project. NASA will use its best efforts to facilitate the issuance of visas to European astronomers and ESA contractors collaborating in the ST Project. ARTICLE 14 Data rights Use of ST scientific data for scientific analysis will be reserved to investigators for a twelve month period, beginning with the receipt of data and any associated spacecraft data in a form suitable for analysts. Investigators may occasionally be requested to share data to enhance efficient utilization of the observatory and of ground observing operations. Immediately after the period reserved to the investigator,reduced data will be deposited with the National Space Science Data Center (NSSDC) and with the science operations facility. In addition, European investigators will deposit their data in the Data Library of the European Space Operations Center (ESOC). Such records will then be available to the international scientific community through the World Data Center for Rockets and Satellites. It is agreed that a listing of all observations will be published at least every six months in sources readily available to astronomers.

EXPLORING THE UNKNOWN 679 ARTICLE 15 Publication of Results Subject to the provisions of Article 14 above, results of the experiments will be made avail- able to the scientific community in general through publication in appropriate journals or other established channels as soon as possible and consistent with good scientific practice. Reprints of scientific and technical reports and publications resulting from this project will be exchanged between ESA and NASA. In the event that such reports or publications are copyrighted, ESA and NASA shall have a royalty free right under the copyright to reproduce and use such copyrighted work for their purposes. Final reports and publications will be placed in the Data Library of ESOC and in the science operations facility. ARTICLE 16 Public Information Each Agency may release information to the public regarding its own activities covered by this Memorandum of Understanding. Each Agency undertakes to coordinate with the other in advance those public information activities which relate to the other Agency's responsibilities or performance in the ST project. Implementing arrangements for these public information activities will be agreed separately. ARTICLE 17 Limits of Obligation It is understood that the ability of ESA and NASA to carry out their obligations under this Memorandum of Understanding is subject to the availability of appropriate funds. ARTICLE 18 Disputes 1. Any dispute as to the interpretation or implementation of the terms of this Memorandum of Understanding shall be referred to the NASA Administrator and the Director General of ESA for settlement. 2. Should the NASA Administrator and the Director General of ESA be unable to resolve such disputes, they will be submitted to such other form of resolution or arbitration as they may agree. ARTICLE 19 Liability 1. NASA shall bear responsibility for damage to US nationals in the course of this coop- erative project, unless such nationals are employees of ESA. 2. ESA shall bear full responsibility for such damage to ESA employees. 3. NASA shall be liable for damage to those items delivered to it by ESA in accordance with Article 4, after the accomplishment of the relevant receiving inspections defined in the NASA/ESA ST Project Plan, but shall not be liable for damage occurring to such items in connection with the Space Shuttle launch, flight or descent. 4. In the event of damage to other persons or property, for which damage there is lia- bility under international law or the principles of the Convention on International Liability for Damage caused by Space Objects, NASA and ESA shall consult promptly on an equitable sharing of any payments that have been or may be agreed in settle- ment. If agreement is not reached within 180 days, the two Agencies will act prompt- ly to arrange for early arbitration to settle the sharing of such claims following the 1958 model rules on arbitral procedure of the International Law Commission. ARTICLE 20 Patent use Authorization, Consent and Indemnification 1. In order to avoid any possible interruption to the conduct of this cooperative project which might arise from patent infringement litigation in U.S. Courts, NASA hereby gives authorization and consent (without prejudice to any rights of indemnification) for all use or manufacture by ESA of any invention described in and covered by a patent of the United States in the performance of any obligations under this Memorandum of Understanding, including the performance of any such obligations by any contractor or subcontractor, providing such use and manufacture is confined entirely to the discharge of the obligations of this Memorandum of Understanding. 2. In the event any liability is incurred by the US Government for the practice of inven- tions covered by privately owned U.S. patents, either as royalties owed under an exist- ing patent license inuring to the benefit of NASA or as judgement and litigation costs resulting from a suit for patent infringement in the U.S. Court of Claims, and such lia- bility is incurred as a result of ESA's and/or any of its contractors' or subcontractors' performance of obligations under this Memorandum of Understanding, or as a result of NASA's use under this Memorandum of Understanding of the items furnished by ESA under this Memorandum of Understanding, ESA agrees to indemnify NASA or any other U.S. Agency against, and make reimbursement for such royalties and/or costs. ESA shall provide such information and assistance as it has available in the defense of any such. patent infringement suit brought in the U.S. Court of Claims. ARTICLE 21 Amendments Each party may propose to the other amendments to this Memorandum of Understanding in writing. Agreements on such amendments shall be established by the parties in the form of riders to this Memorandum of Understanding. ARTICLE 22 Termination This Memorandum of Understanding shall enter into force when both the NASA Administrator and Director General of ESA have signed it, and it shall remain in effect for

EXPLORING THE UNKNOWN 681 a first period of eleven years from the first launching of the ST. It is anticipated that this period wilt include at least ten years of ST space operations. At least one year, before the expiration of the eleven year period, the parties agree to consult as to continuation or ter- mination of this Memorandum of Understanding. The Memorandum of Understanding will continue in its present form unless it is terminated or amended. For the National Aeronautics and Space Administration [signature] R. Frosch For the European Space Agency [signature] R. Gibson 7 October 1977 7 October 1977 Document III-30 Document title: Post Launch Mission Operation Report to NASA Administrator from Thomas A. Mutch, NASA Associate Administrator for Space Science, August 16, 1979. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. After NASA's fourth Small Astronomy Satellite, an ultraviolet mission, was postponed due to budget constraints, the space agency teamed with the European Space Research Organization (later the European Space Agency [ESA]) and the United Kingdom's Science Research Council to redefine the project, which became known as the International Ultraviolet Explorer (IUE) mission. Launched from the United States in 1978, IUE succeeded in meeting all of its scientific objectives. IUE became one of the world's most successful astronomy missions ever, generating more than 3,000 scientific papers among astronomers worldwide. Although the satellite was still operating well twenty years after launch, it was turned off so funds for its operation could be used for other space science purposes. [no page number] TO: A/Administrator Post Launch Mission Operation Report No. S-868-78-03 August 16, 1979

682 NASA AND PLANETARY EXPLORATION FROM: S/Associate Administrator for Space Science SUBJECT: International Ultraviolet Explorer (IUE) Post Launch Report #2 The International Ultraviolet Explorer (IUE) is adjudged successful based upon the results of the mission with respect to the approved prelaunch objectives. The IUE, an Explorer-class ultraviolet astronomy mission, is an international cooper- ative program between the United States, the United Kingdom (UK), and the European Space Agency (ESA) which provides for a single launch into a geosynchronous orbit to conduct spectral distribution studies of celestial and solar system ultraviolet sources. The spacecraft and scientific instrument were [sic] designed and fabricated at the Goddard Space Flight Center. The spectrograph camera system was provided by the UK; ESA pro- vided the Solar Array as well as the European Ground Station. The available observing time is shared roughly equal to the respective contributions, with the US having two-thirds and the UK and ESA sharing equally in the remaining one third. The IUE observatory system was designed to functionally resemble a ground-based optical observatory at which guest observers could execute observing programs in real time. Observations are made from ground stations at GSFC and Madrid, Spain. In the 15 months since IUE commenced routine guest observer operations on April 3, 1978, Observatory performance has substantially exceeded design and mission objec- tives. At high resolution, spectra of stellar sources has been obtained as faint as 12th mag- nitude while at lower resolution, observations have been made of extragalactic sources fainter than 17th magnitude. The latter observations required 3-axis stabilized pointings in excess of 14 hours continuously. The secondary mission objectives have also been met. The IUE gyros have been select- ed for Space Telescope (ST) use; the IUE Spectrograph is a forerunner of the ST High Resolution Spectrograph; the IUE cameras have influenced the design of detectors for the ST Faint Object camera; and the IUE operational software and guest observer operations will provide an experience base for ST. In addition to the high quality of the output, the data productivity is also great. NASA guest observers have obtained over 6000 images supporting more than 100 different research programs. The UK and ESA guest observers have produced almost 3000 images in support of 150 or so research programs. As a result, scientific results are [2] being wide- ly reported. Well over 100 papers have been presented at various meetings and symposia both in this country and abroad. By the time of the first anniversary in orbit, January 1979, 15 publications had already appeared in NATURE and the Astrophysics Journal Letters (Attachment). [not included] Many more have been published or are in preparation (Attachment 2 is a partial summary of results from NASA observers). [not included] A summary of a selected number of the most important results obtained to date fol- lows: a. Discovery of mass loss in hot subdwarfs and of “cool” stellar winds in G and K supergiants.

 b. Delineation of the region in the HR diagram exhibiting chromospheric phe- nomena. c. Discovery of short-term variability in line profiles of OB supergiants. d. Discovery of gold in A peculiar stars. e. Detection of CR II in the interstellar medium. f. Discovery of hot circumstellar shells around stellar X-ray sources. g. Discovery of bright UV sources at the centers of some globular clusters. h. The first ultraviolet observations of a recurrent nova indicating that the ejected mass is an order of magnitude less than for classical novae. i. The first ultraviolet spectra of a supernova. j. The first ultraviolet spectra of supernova remnants. k. The first direct observational evidence of a high temperature corona about our galaxy indicating Te ~ 105 and Ne ~ 4 x 10-4. 1. Observations of UV line intensities for several low and intermediate redshift QSO's; detection of continuum radiation in two high redshift QSO's down to rest wavelengths below 400 A. m. Discovery of acetylene in the atmosphere of Saturn. n. Discovery of ultraviolet limb brightening on the Jovian disc, requiring the exis- tence of an extensive pure Rayleigh atmosphere. IUE performance continues to be excellent. The only expendable limitation to IUE lifetime is the onboard hydrazine for momentum wheel unloading and station keeping. At the present usage rate, IUE could last for 30 years. All the essential spacecraft subsys- tems are redundant; the only failure that has occurred is in a redundant Panoramic Attitude Sensor (PAS), but the PAS is not required for in-orbit operations. Some anom- alies have occurred with the onboard computer (OBC) but they have been corrected through internal reprogramming. It should be noted that during the course of the anom- alies, backup and survival modes were implemented successfully. [3] Scientific Instrument performance has also been excellent. The only problem is with a redundant Short Wavelength Spectrograph Camera which operates intermittently. Both Long Wavelength Spectrograph cameras are operational as are both Fine Error Sensors. In summary, the IUE is working very well and shows every expectation of continuing. The great productivity and large number of exciting and even unexpected results consti- tute a substantial scientific and technical achievement and give promise to future sub- stantial scientific results. [signature] Thomas A. Mutch

684 NASA AND PLANETARY EXPLORATION Document III-31 Document title: The Management Operations Working Group for Space Astronomy, NASA, "Space Astronomy Program Plan for the 1980s and 1990s," July 1981. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. As NASA entered the 1980s, there was a perceived need to define a new astronomy program for the rest of the twentieth century. Astronomers felt ready to design space missions to address some of the fundamental scientific questions about the origin and evolution of the universe. [cover sheet] [i] PREFACE SPACE ASTRONOMY PROGRAM PLAN FOR THE 1980S AND 1990s The Management Operations Working Group for Space Astronomy July, 1981 Space astronomy is on the threshold of a new era of exploration. Over much of the electromagnetic spectrum, surveys during the past two decades have systematically mapped out the wonders of the Universe. Future missions must confront the challenge of understanding the complexity and physical nature of the diverse astrophysical objects that astronomers have already begun to catalogue. Only by firmly grasping the unique per- spectives provided by space astronomy can we hope to solve the great mysteries and unfold the grand designs that determine the evolution of stars and galaxies. Exciting problems that may be resolvable over the next two decades include the nature of the underlying energy source in quasars and the nuclei of active galaxies, the origin and eventual fate of the Universe, and the mechanism of stellar birth and planetary system formation. The great questions which express our curiosity about our cosmic environment often persist unanswered for generations. What factors determine the long-term climactic vari- ation on Earth? Has intelligent life evolved elsewhere? Will the Universe end in a cata- clysmic collapse, will all life eventually succumb to entropy, or will the expansion of the Universe offer infinite scope for suitably evolving intelligences? Are the laws of physics, which underpin our attempts to understand Nature, truly eternal and universal? The means by which we seek to answer such questions, and the myriad subsidiary questions, change almost every decade. In this report, we present a plan for the U. S. space astronomy program, with specific projects for the near future, development programs for subsequent projects, and projects which await a more extensive presence in space.

EXPLORING THE UNKNOWN 685 ******** [63] V. RECOMMENDATIONS This chapter describes recommendations made by the MOWGSA [Management Operations Working Group for Space Astronomy] regarding the implementation of mis- sions and programs discussed in the proceeding [sic] chapters, and summarizes those rec- ommendations (Section V.A). In a later section (V. B), a brief review of the recommended missions and their impact on the science goals outlined in Chapter 1 is presented, show- ing which of those goals will be accomplished by the recommended program. A. Summary of Recommendations The MOWGSA has discussed programs and missions that fall into several general cat- egories: current flight programs (Section II.A); pending flight programs (II.B); support- ing programs (II.C); future missions (Chapter III); and technology development (Chapter IV). These categories are summarized separately in the following paragraphs. 1. Current Flight Programs Programs considered current are those that are already funded and under develop- ment. These include the Space Telescope (ST), the Infrared Astronomical Satellite (IRAS), Spacelab and Shuttle experiments, and the Explorer program. The MOWGSA considers all of these programs to be important and endorses each. The Space Telescope will be the mainstay of the U. S. space astronomy program for the rest of this century, and the MOWGSA heartily endorses it and urges that every effort be made to provide opportunities for refurbishment and upgrading of the focal-plane instruments. The Infrared Astronomy Satellite will provide the first comprehensive survey of the heavens at far-infrared wavelengths, and will therefore set the stage for a new era of infrared astrophysics by locating and determining the properties of some 10 sources. In addition to endorsing ST and IRAS, the MOWGSA has agreed upon the following specific recommendations regarding the Explorer and Spacelab programs: that the Explorer program should have enhanced funding, at least sufficient to recover losses to inflation over the past decade; and that the Spacelab program should be augmented, allowing more numerous flight opportunities. 2. Pending Flight Programs Pending flight projects are those currently in the NASA five-year plan, but not yet under development. These include the Cosmic Background Explorer (COBE), the Extreme Ultraviolet Explorer (EUVE), and the Shuttle Infrared Telescope Facility (SIRTF). Again, the MOWGSA endorses all of these programs, and makes one specific rec- ommendation: that funding for SIRTF be significantly enhanced, [64] providing for many more refurbishments and flights than currently planned. The SIRTF, with its broad poten- tial wavelength coverage and the versatility to support a great variety of focal-plane instru- ments, will open new areas of astrophysics for infrared astronomy, and could form the backbone of future infrared observational programs if the community is given sufficient opportunities to take full advantage.

 3. Supporting Programs These are programs that provide various kinds of support services, often with direct scientific benefits, and in other cases with significant indirect effects. Among the former are the suborbital programs (sounding rockets, balloon and airborne astronomy) and the- oretical astrophysics, while the latter includes laboratory astrophysics, some aspects of data analysis, and the funding of scientific personnel. The MOWGSA endorses continued support for all of these programs, but particu- larly emphasizes a few. One of these is the continued provision for the development of new instrumentation, through the suborbital programs, or eventually the Experiments of Opportunity Payloads (EOP) program. It is vital for the entire space astronomy pro- gram that support be provided to PI-class investigators for the development of new instruments, because this is the most efficient way to test new concepts without com- mitment to a major mission. The MOWGSA has made no attempt to recommend a spe- cific balance among the programs that fall into this area, but simply emphasizes the importance of the overall concept. Among the other supporting programs, the MOWGSA specifically makes recommen- dations for the augmentation of support for: theoretical astrophysics, because of its impor- tant, but sometimes overlooked, rate both in planning new missions and in the interpretation of data; laboratory astrophysics, because there is an increasing need by astrophysicists for atomic data relevant to the interpretations of new observational areas (such as the extreme ultraviolet), while at the same time there are increased difficulties (due in part to lack of support) in successfully encouraging atomic and molecular physi- cists to provide the needed data; and data-analysis, because of the growing complexity and quantity of scientific data being returned by space missions, particularly with the advent of two-dimensional electronic detectors. 4. Future Missions Generally speaking, a mission or mission concept was assigned to one of three rec- ommended classes: (1) highly recommended, meaning that the MOWGSA feels strongly that the program should be implemented (or at least formally studied) as soon as possi- ble; (2) recommended, meaning that the program is desirable and should become a part of NASA's planning, so that opportunities for implementation may be sought and taken when possible; and (3) concept to be studied, meaning that the idea has sufficient merit to justify some expenditure of resources in developing the concept to a point where its feasibility and importance may be adequately assessed. [65] Table V.I. Future Missions Mission Far-UV Spectroscopic Explorer (FUSE) Large Deployable Reflector (LDR) CB Status Cost Class* Readiness Category Highly recommended A Highly recommended II III Highly recommended ■ I Highly recommended A II Simultaneous Astrophysics Mission (SAM) Planetary Spectroscopy Telescope Recommended A I Recommended A I Orbiting VLBI Mission Relativity Explorer (REX)

EXPLORING THE UNKNOWN UV Wide-Field Imaging Mission Very Large Space Telescope (VLST) Optical Interferometry Mission Molecular Astrophysics Pencil-Beam Explorer (MAPPER) Solar Sail Telescope Recommended A I Extreme UV Spectroscopic Explorer (EUSE) Concept for study A-B IV Concept for study C IV Concept for study A-B III Concept for study A-B III Concept for study Laser Gravitation Wave Antenna Concept for study Orbiting Eotvos Experiment Large Airborne Telescope (LAT) Concept for study Concept for study ABAA ■ 22EE IV IV III III 687 *Cost Classes: A: < $100 M B: $100 500 M C: > $500 M *Technological Readiness Categories: I. Technology already demonstrated in flight. II. Technology known; not yet used in flight. III. Concepts well developed; not yet demonstrated. IV. Concepts not yet fully developed. [66] The missions that have been discussed in Chapter 3 are summarized in Table V.1, where the MOWGSA recommendation category, as well as a technological readiness cate- gory and a broad cost-class estimate are also presented. The definition of both the readi- ness and cost classes are given in footnotes to this table. The MOWGSA has identified four future missions that are given "highly recom- mended" status. The committee has not prioritized among these four, so no specific rec- ommendation regarding their sequence can be given. Most likely, the technological readiness and the method of funding (e. g. whether or not a mission can be developed as an Explorer, or whether there is partial support from abroad) will ultimately dictate the schedule for implementation of these missions. The Far-Ultraviolet Spectroscopic Explorer (FUSE) mission is a natural and neces- sary-adjunct to such past and present programs as Copernicus, IUE, and Space Telescope, providing as its highest priority high-resolution spectroscopy between 912 A and 1200 A, a region rife with important features for both stellar and interstellar problems but not cov- ered by IUE or ST, and only weakly covered by Copernicus. The Large Deployable Reflector (LDR) will provide infrared and millimeter-wave astronomers with a powerful tool for exploring important new wavelength regions, attaining high spatial resolution. The Very Long Baseline Interferometry (VLBI) Explorer will allow a baseline for high spa- tial-resolution radio mapping with coverage of much of the sky, something not possible with ground-based VLBI measurements. The Relativity Explorer (REX) will measure two new gravitational effects (geodetic effect and motional effect) in earth orbit to test gravi- tational theory. An additional three missions are listed as “recommended”. Again, no prioritization within this group has been made.

 A Simultaneous Astrophysics Mission (SAM) would provide simultaneous observa- tions of variable stars and other objects in the soft x-ray, ultraviolet, visible, and possibly the near-infrared regimes, so that different physical regions in these objects can be mon- itored at the same time. The Planetary Spectroscopy Telescope would be optimized to pro- vide spectroscopic data on planetary atmospheres, allowing synoptic studies and those requiring special pointing that are not feasible with other instruments. After lengthy dis- cussion concerning the UV imaging missions that were considered, it was decided to treat as distinct missions two alternatives: a wide-field survey intended to eventually cover the entire sky; and a moderate-field imager with superior sensitivity and spatial resolution, for detailed studies of specific fields. A consensus was reached that the former, the wide-field survey, should be given higher priority, but that the latter should also be encouraged. A full-sky survey in ultraviolet wavelengths would provide a natural extension towards short wavelengths of the kind of information available in the Palomar Sky Survey, and would become a fundamental storehouse of information that would be especially important in the era of Space Telescope. The moderately wide-angle imaging experiment was also gen- erally favored, but is probably not of sufficient importance to be considered for support unless NASA obtains substantial participation from abroad. In addition, it is recommended that every opportunity be utilized to perform add-on gravitational physics experiments in conjunction with interplanetary missions including search for gravitational radiation, precision radio tracking of planetary orbiters and lan- ders, and relativity experiments on the proposed Star Probe. [67] Finally ten more possible future missions were chosen to be listed as "concepts for study," in this case with some rough prioritization. Five of these ten were placed in a high- er priority category: these five are the Extreme Ultraviolet Spectroscopy Explorer (EUSE), the Very Large Space Telescope (VLST), gravity wave experiments using laser interfer- ometry, the Large Airborne Telescope (LAT), and an optical interferometry mission. The MOWGSA recommends particularly highly the study of these five possible missions, and urges that funding for such studies be provided as soon as possible. 5. Technology Needs In the course of its study of possible future programs, the MOWGSA identified sever- al general areas of technology development, which will be required by one or more of the recommended missions. No prioritizations among these areas were attempted, and here they will only briefly be summarized. Most are already under development at some stage; the MOWGSA's endorsement is meant to emphasize the needs and, in specific cases, calls for enhanced support. The MOWGSA urges the development of space platforms, to serve as support systems for long-term (e.g. 6-month) orbital experiments. This is a natural follow-up to the Spacelab program which will support short-duration flight, and may also be a step in the direction of permanent manned space stations. The space platform should provide some sort of pointing capability as well as power. Another area of interest to the MOWGSA is the development of suborbital platforms, such as the semi-buoyant aircraft described in the discussion of the Large Airborne Telescope (Appendix) [Appendix not included]. Telescopes placed in the atmosphere above 40,000 feet would have significant capabilities, both in wavelength coverage and in

EXPLORING THE UNKNOWN 689 spatial resolution, and would be useful tools throughout the spectrum from the near-ultra- violet far into the infrared. The potential for maintaining heavy payloads at these altitudes for long periods with minimal fuel expenditure is very attractive. The MOWGSA also encourages the development of generalized spacecraft pointing and control systems, which could be applicable in many situations, thereby reducing the cost of development of such systems as needed for individual missions. This would have application to a wide variety of situations, including the space platform mentioned above. The general area of detector development, which already receives significant support, is an important one which the MOWGSA feels should be augmented. At present NASA is unable to support competitive parallel development of detector concepts, generally being forced instead to limit funding to one development program for each type of detector. This does not necessarily ensure that the best possible detector is produced in the end, nor does it allow NASA the flexibility to pursue new concepts when they arise. To support this program at a higher level will be of paramount importance, until the time when pho- ton-counting area detectors with the highest theoretically-possible quantum efficiency have been developed for each wavelength region of interest. Another area of concern to the MOWGSA is the development of optical systems for space astronomy, including optical surfaces and coatings, the development of [68] filters of various kinds, and the design of optimized optical system needed for the various mis- sions recommended for future implementation. Data management, already mentioned under supporting programs, will require some technology development. This includes not only hardware devices such as image display systems, fast data lines, and super-compact storage device, but also the development of data management systems. The need for increased support in these areas grows with the launch of each new instrument, and will make a quantum jump when ST is in operation. The MOWGSA also recognizes the need for technology developments in support of various gravitational physics experiments, many of which are recommended in this report. The needs include the development of cryogenic technology, stable clocks, and radio ranging and doppler tracking systems for experiments flying aboard interplanetary probes. Finally, the MOWGSA encourages support for the study of technology for interstellar flight. This refers to unmanned probes to nearby stars, which could sample and report; on conditions and materials in interstellar space, as well as obtaining close-up data on other stars. While such a mission is obviously far in the future, it is appropriate to begin related studies soon. Of particular importance is the need to study possible propulsion systems. B. Impact on the Science Program Having made its recommendations, the MOWGSA felt that it would be useful to sum- marize here how the recommended program fulfills the science goals outlined in Chapter I. The following paragraphs briefly do so, taking things in the sequence established in that chapter. 1. Cosmology The principal missions discussed in this report that will have an impact on cosmology are: COBE, which will make accurate measurements of the spectrum and isotropy of the cosmic background radiation; LDR, which will attempt to measure the anisotropy of the cosmic background; FUSE, which will be capable of directly measuring the D/H ratio towards distant and/or reddened stars; and ST, which will make enormous strides towards measuring intergalactic gas and the study of primordial galaxies. The latter goal will not only have direct bearing on the properties of the Universe as a whole, but will also be important for studying galactic evolution, as mentioned below. SIRTF, IRAS, COBE, and LDR will yield information on the properties of very young galaxies whose emission is red- shifted all the way into the infrared or millimeter-wave portions of the spectrum. All of these missions, except for LDR and FUSE, are already either under develop- ment or pending, LDR and FUSE are among the most highly recommended future mis- sions. [69] 2. Gravitation The Objective of gravitational physics experiments and missions is the investigation of relativistic gravity effects to test gravitational theories. Relativistic gravitation plays a major role in many astrophysical phenomena and in cosmology. The highly recommended REX mission will measure the frame dragging or mass current effect which is the gravitational counterpart to electromagnetism. This phenomenon, which is important for fast rotating and dense astrophysical objects, has not been measured yet. The proposed Star Probe mis- sion would provide an opportunity to measure relativistic gravitational effects in the strong gravity field close to the Sun and to determine the solar quadrupole moment to high accuracy. The Mercury Orbiter mission would provide an alternate way for accurate determination of the solar quadrupole moment and of the relativistic perihelion advance. Add-on gravitational experiments on planetary lander missions would provide unique opportunities for long term observations of relativistic effects in the motion of planets and to test the constancy of the gravitational constant. The search for gravitational radiation is a very important scientific objective. Search for low frequency gravitational radiation can be done by precision radio doppler tracking of interplanetary space probes. A much more sensitive detector would be a laser gravita- tional wave antenna in space, a proposed future mission requiring rather advanced tech- nology. Other proposed future missions would perform extremely high precision measurements of relativistic effects to probe for the limit of validity (possible breakdown) of gravitational theories: a test of the relativistic deflection of light to second order could be accomplished with the POINTS mission and an extremely sensitive test of the Weak Equivalence Principle with the Orbital Cryogenic Eötvös Experiment. 3. Galaxies and Galactic Evolution The strongest tool proposed for studies of galaxies and galactic evolution is ST (under development) which will provide spectroscopy and high-resolution imagery of galaxies and galactic nuclei, with potential for studying all the related problems of chemical enrichment, stellar and galactic winds, stellar populations, and the diffuse interstellar medium. In addition, a VLBI mission (highly recommended) would yield a wealth of information on morphology of galaxies; and in the infrared, IRAS, SIRTF, COBE, and the LDR (highly recommended) would all contribute to studies of the distribution of pri- mordial galaxies and their spectral energy distributions, as well as the distribution of dust

EXPLORING THE UNKNOWN 691 and star-formation regions within nearby galaxies. Variability in galactic nuclei would be usefully observed with the SAM, (recommended), while both the wide-field and moder- ate-field UV-imaging missions (both recommended) would contribute enormously to studies of the morphology and chemical evolution and gradients of galaxies. FUSE (high- ly recommended) would provide data on the far-UV spectra of galactic nuclei, as well as on the interstellar gas and dust in nearby galaxies. The heavily-obscured regions in galaxies could be probed with HAS (under develop- ment); SIRTF (pending), and LDR (highly recommended) which will penetrate these regions, providing photometry on objects inside as well as spectroscopy of both the embedded objects and the intervening interstellar material. A large airborne observatory with infrared capabilities (concept for study) would allow [70] significant work to be done in these areas from a suborbital platform, and the MAPPER mission (concept for study) would trace the distribution of molecular clouds in nearby galaxies, as well as our own. Finally, FUSE (highly recommended) would significantly extend coverage of the diffuse interstellar medium, by probing far-UV wavelengths where a number of important transi- tions lie, inaccessible to ST or IUE. The EUSE (concept for study) would extend this even further towards short wavelengths, providing coverage of more highly-ionized species in the coronal gas. 4. Stellar Research A number of the missions mentioned in the galactic astronomy section will. also be important tools in stellar astrophysics. Stellar flux distributions will be determined by IRAS (under development) and EUVE (pending), while spectroscopy will be carried out from the infrared (SIRTF; pending) to the ultraviolet (ST, under development; and FUSE, highly recommended) and possibly even the extreme ultraviolet (ELISE, concept for study). The development of the VLST (concept for study) and the LDR (highly recom- mended) will augment both areas by allowing an extension to fainter objects. Stellar chromospheres and coronae will be especially well studied by FUSE (highly recommended) and ELISE (concept for study, covering a wide range of highly-ionized species, and extended atmospheres in cool stars will be observed efficiently with SIRTF (pending) and LDR (highly recommended). Stellar winds will best be observed in the UV (with ST; under development) and the far-UV (FUSE; highly recommended), and infrared data from HAS (under development), SIRTF (pending), and the LDR (highly recommended) will also be important in probing the interactions between the interstel- lar medium and winds from embedded stars. In all manner of variable star research, SAM (recommended) will play an important role by providing simultaneous observations of activity in different wavelength regions, hence different layers in stellar atmospheres and envelopes. Finally, the extension to fainter stellar objects by many of the recommended instru- ments, particularly ST, will allow studies of individual stars in nearby galaxies, opening the way for analyses of the effects on stellar properties of galaxy type and evolution. 5. Planetary Astronomy Many of the instruments and missions discussed in this report will have important applications to studies of solar system objects. ST (under development) will provide high-resolution images of planets, extending studies of atmospheric motion begun with the Pioneer and Voyager probes, and will be capable of detecting certain classes of planets orbiting nearby stars. FUSE (highly recommended) could provide important ultraviolet spectroscopic data on planetary atmospheres, as could SIRTF (pending) and LDR (high- ly recommended) in the infrared. Great contributions to the study of the planets, partic- ularly synaptic studies of their atmospheres, would be made by the Planetary Spectroscopy Telescope (PST; recommended), [71] which would have pointing and scheduling char- acteristics optimized for such studies. Finally, spectroscopy of comets could be accomplished by a variety of missions such as ST (under development), FUSE (highly recommended), SIRTF (pending), and LDR (highly recommended) all of which will be sufficiently sensitive not only for emis- sion-line measurements, but also for absorption-line observations, using background stars as continuum sources. 6. SUMMARY Nearly every major research goal outlined in Chapter I can be accomplished, at least in part, by missions described in this report. A large fraction will be carried out by those listed as "under development", "pending", "highly recommended”, or “recommended", so that prospects are strong for accomplishing much of what the MOWGSA sees as desirable before the end of this century. The success of this program depends not only on the spe- cific missions mentioned in this section, but also on the supporting programs and tech- nological developments outlined earlier. The MOWGSA hopes that this planning document will prove to be useful in the com- ing years, as NASA seeks to carry its functions in space astronomy. Document III-32 Document title: Gamma-Ray Observatory Science Working Team, The Gamma-Ray Observatory Science Plan, September 1981. Source: Alan Bunner, Office of Space Science, NASA Headquarters, Washington, D.C. The Space Science Board endorsed the development of a major space-based facility devoted to gamma- ray astronomy in 1976. A year later, NASA released an announcement of opportunity inviting sci- entists to propose instruments for the spacecraft, which became known as the Gamma-Ray Observatory (GRO). While five instruments were tentatively selected for definition studies, that list was narrowed to four when one of the experiments could not meet cost and programmatic constraints. President Jimmy Carter in 1979 approved the GRO for development in preference to a U.S. mission to comet Halley, because he was convinced that it would produce more important scientific data than would a comet mission. In September 1981, the GRO Science Working Team developed this science plan in light of the four experiments selected and the goal to keep total mission costs below $100 million (FY 1981 dollars). These four instruments made up the payload of spacecraft, which took the name

EXPLORING THE UNKNOWN 693 Compton Gamma Ray Observatory, after physicist Arthur Holly Compton, when it was launched aboard the Space Shuttle in 1991. The Compton GRO spacecraft was purposely deorbited in 2000 because its control gyroscopes were failing. [cover sheet] THE GAMMA-RAY OBSERVATORY [1] SCIENCE PLAN SEPTEMBER 1981 Prepared by: Gamma-Ray Observatory Science Working Team GAMMA-RAY OBSERVATORY SCIENCE PLAN I. INTRODUCTION Gamma-ray astronomy, the study of the highest energy electromagnetic radiation from the cosmos, occupies a unique position in the search for understanding the Universe. This high energy radiation is produced in a wide variety of astrophysical processes which would otherwise remain unobservable. These processes include nuclear reactions, matter-antimatter annihilation, elementary particle decays, and some general relativistic effects. The great penetrating power of gamma rays allows them to reach the top of the atmopshere [sic] from almost anywhere in the Universe. On the other hand, the atmopshere [sic] is opaque to gamma rays, and, hence, the observations must be made from space. The astrophysical sites where gamma-ray emission is a major source of energy release are some of the most energetic objects in the Universe-e.g., supernovae, neutron stars, black holes, cores of galaxies, and quasars. Among the problems addressed by gamma-ray astronomy are the formation of the elements in the Universe, the structure and dynamics of the Galaxy, the nature of pulsars, the possible existence of large amounts of antimatter in the Universe, phenomena occurring in the nuclei of galax- ies-especially explosive galaxies-and the origin and evolution of the Universe itself. For many such problems, gamma rays are the only source of information about the high energy reactions taking place. Because gamma-ray astronomy requires complex detectors operating outside the Earth's atmosphere, it is only in recent years that this field has begun to develop. The dis- coveries in gamma-ray astronomy parallel those in other new branches of astronomy in that the unexpected results have been as significant as those which had been predicted in providing new insight into a number of astrophysical problems. [2] For example, it has been found that some pulsars emit several orders of magnitude more energy in the form of gamma rays than in the form of radio waves and that the quarsar [sic] 3C273 appears to radiate as much energy in gamma rays as in any other form of electromagnetic radiation. Also, many energetic gamma-ray sources have been found which at present have not been correlated with objects observed at other wavelenghts [sic]. These observations suggest the possibility of a class of celestial objects not previous- ly known. Further, intense bursts of low energy gamma rays have been detected; the origin of these events remains a mystery. In all these cases, these objects cannot be fully understood without a thorough knowledge of their gamma-ray emission, because this emission represents such a significant fraction of the total radiated energy. The under- standing of gamma-ray-luminous sources is one of the most important open problems for all astronomy. Other important astronomical questions for which gamma-ray astronomy can provide decisive answers include nucleosynthesis, via the study of gamma-ray line emission; Galactic structure, as revealed by the gamma rays produced in the interactions of cosmic rays with interstellar matter; and the origin and evolution of the Universe, through obser- vations of the isotropic gamma radiation. Beyond these known returns lies the anticipa- tion of further unexpected results in gamma-ray astronomy as the sensitivity of the observations improves, particularly because much of the gamma-ray energy range is just now being explored and much of the gamma-ray sky has not been observed. The Gamma-Ray Observatory (GRO), which will provide the first comprehensive, coordinated observations covering the entire spectrum of gamma-ray astronomy, with much better sensitivity than any previous mission. [sic] This approach requires four sepa- rate detector systems with quite different characteristics, each emphasizing a particular aspect of the observations. [3] In this Science Plan for the GRO, Section II [not included] discusses in depth the sci- entific rationale for gamma-ray astronomy. Section III presents the specific scientific objectives for the GRO and describes how the four selected instruments have a combined capability to achieve these objectives. Section IV [not included] contains a summary of each of the four investigations chosen for the mission. ******** [21] A. Scientific Objectives III. GAMMA-RAY OBSERVATORY Based on the foregoing scientific rationale and the recommendation of the Committee on Space Astronomy and Astrophysics of the National Academy of Science's Space Science Board, GRO has adopted the following scientific objectives: • . • . A study of discrete objects such as black holes, neutron stars, and objects emitting only at gamma-ray energies. A search for evidence of nucleosynthesis - the fundamental process in nature for building up the heavy elements in nature and other gamma-ray lines emitted in astrophysical processes. The exploration of the Galaxy in gamma rays in order to study the origin and dynamic pressure effects of the cosmic-ray gas and the structural features revealed through the interaction of the cosmic rays with the interstellar medium. A study of the nature of other galaxies as seen at gamma-ray wavelengths, with spe- cial emphasis on radio galaxies, Seyfert galaxies and QSO's. A search for cosmological effects, through observations of the diffuse gamma radiation, and for possible primordial black hole emission. Observations of gamma-ray bursts, their luminosity distribution, the spectral and temporal characteristics and their spatial distribution.

EXPLORING THE UNKNOWN 695 [22] In the section that follows, a brief description of the observatory requirements nec- essary to achieve these objectives, the specific spacecraft parameters needed to support these requirements and a brief description of the instruments to be used in these obser- vations will be presented. B. Observatory Requirements To achieve these scientific objectives, the Gamma-Ray Observatory must be capable of conducting a comprehensive survey of the gamma-ray sky over an energy range extending from the upper end of existing x-ray observations up to the highest practical energy. The GRO sensitivity for discrete sources, diffuse radiation, and gamma-ray lines should be sig- nificantly greater than any previous instruments. No single scientific instrument is capable of meeting all the requirements. The band of wavelengths encompassed by gamma-ray astronomy is more than 100 times as broad as that of x-ray astronomy, and more than 104 times broader than the visible region. Different detection methods are needed in different parts of the gamma-ray spectrum. Further, even within a part of the energy range, energy and angular resolution can usual- ly be improved only at the expense of sensitivity. A complementary set of experiments is required, therefore, in order to meet the scientific objectives. The spacecraft supporting these instruments must be capable of pointing them accurately and with stability to any part of the sky for a period of two weeks, provide adequate power and thermal control, supply attitude and timing data as precise as needed by the instruments, and handle the data from all these instruments efficiently. [23] C. Spacecraft Summary The Gamma-Ray Observatory will be a shuttle-launched, free-flyer satellite. The nominal circular orbit will be about 400 kilometers with an inclination of 28.5°. The radius should remain below 450 kilometers to prevent excessively high trapped particle dosages during passage through the South Atalantic Anomally [sic]. An orbital radius below about 350 kilometers causes excessive aerodynamic drag on the Observatory. The spacecraft must be capable of accommodating 5500 kilograms of instruments and must supply 600 watts of experiment power. The 17 kilobits per second of experiment data will be supported via NASA's Tracking and Data Relay Satellite system. Celestial point- ing to any point on the sky (excluding the Sun) will be maintained to an accuracy of ±0.5°. This is determined by the precision to which exposure to a given region of the sky must be known in order to determine the sensitivity of an observation. Knowledge of the pointing direction will be determined to an accuracy of 2 arc minutes so that this error contributes negligibly to the over all determination of the direction of gamma-ray source. Absolute time will be accurate to 0.1 milliseconds to allow precise comparisons of pulsars and other time varying sources with observations at other wavelengths from ground observations and other satellites. The attitude and timing data together with orbital position will be encoded into the telemetry data. These spacecraft support requirements are summarized in Table I.

696 NASA AND PLANETARY EXPLORATION Table I SPACECRAFT SUPPORT REQUIREMENTS [24] Scientific Payload Weight Instrument Power Experiment Data Rate Pointing Accuracy Attitude Determination Absolute Timing Accuracy 5500 kilograms 600 watts 17 kilobits ±0.5° 2 arc minutes 0.1 milliseconds Brief capsule descriptions of each experiment are given as follows: More detalied [sic] descriptions can be found in Section IV. 1. Gamma-Ray Observatory Scintillation Spectrometer (OSSE): This experiment utilizes four large actively-shielded and passively-collimated-Sodium Iodide (Nal) Scintillation detectors, with a 5° x 11° FWHM field of view. The large area detec- tors provide excellent sensivity [sic] for both gamma-ray line and continuum emissions. An offset pointing system modulates the celestial source contributions to allow background sub- straction. It also permits observations of off-axis sources such as transient phenomena and solar flares without impacting the planned Observatory viewing program. [25] 2. Imaging Compton Telescope (COMPTEL): This instrument is based on a newly established concept of gamma-ray detection in the 1-30 MeV range. It employs the unique signature of a two-step absorption of the gamma-ray, i.e., a Compton collision in the first detector followed by total absorption in a second detector element. This method, in combination with effective charged particle shield detectors, results in a more efficient suppression of the otherwise inherent instru- mental background. Spatial resolution in the two detectors together with the well defined geometry of the Compton interaction permits the reconstruction of the sky image over a wide field of view (~1 steradian) with a resolution of a few degrees. In addition, the instru- ment has the capability of searching for polarization of the radiation. The instrument has good capabilities for the search for weak sources, weak galactic features and for the search for spectral and spatial features in the extragalactic diffuse radiation. 3. Energetic Gamma-Ray Telescope (EGRET): The High Energy Gamma-Ray Telescope is designed to cover the energy range from 20 MeV to 30 x 103 MeV. The instrument uses a multi-thin-plate spark chamber to detect gamma rays by the electronpositron pair process. A total energy counter using NaI(TI) is placed beneath the instrument to provide good energy resolution over a wide dynamic range. The instrument is covered by a plastic scintillator anticoincidence dome to prevent readout on events not associated with gamma rays. The combination of high energies and good spatial res- olution in this instrument provides the best source positions of any GRO instrument. [26] 4. Burst and Transient Source Experiment (BATSE): The Burst and Transient Source Experiment for the GRO is designed to continuous- ly monitor a large fraction of the sky for a wide range of types of transient gamma-ray

 events. The monitor consists of eight wide field detector modules. Four have the same viewing path as the other telescopes on GRO and four are on the bottom side of the instrument module viewing the opposite hemisphere. This arrangement provides maxi- mum continuous exposure to the unobstructed sky. The capability provides for 0.1 msec time resolution, a burst location accuracy of about a degree and a sensitivity of 6 x 108 erg/$cm^2$ for a 10 sec burst. The salient features of the four experiments are summarized in Table II. As men- tioned above, each instrument represents a significant step forward over its predecessors. For example, the sensitivity for line gamma-ray detection has been improved by more than an order of magnitude over the HEAO-A4 and HEAO C-1 instruments. The continuum sensitivity in the MeV range is typically improved by a factor of twenty or more. Improvements of about an order of magnitude in source location capability are also expected due to the improved instruments and the greatly increased exposure factors. The addition of a massive Nal calorimeter crystal has markedly improved the energy res- olution (a factor of 2 better than SAS-2) in the > 100 MeV range and extended the range to 20 GeV. Also in this range the total effective area (i.e., area X geometry factor) is 25 times larger than that of COS-B. [27] Table II SUMMARY OF GRO DETECTOR CHARACTERISTICS OSSE Energy Range (MeV) Energy Resolution Maximum Effective Area 0.10 to 10.0 8.0% at 0.66 MeV 2310 COMPTEL 1.0 to 30.0 5-8% 50 EGRET 20 to 3x104 15% 2000 BATSE 0.05 to 0.60 35% at 0.1 MeV ($cm^2$ efficiency) Position Resolution (strong source) Maximum Effective Geometric Factor ($cm^2$sr effeciency) [sic] Estimated Threshold Line (source sensitivity) 10 arc min square error box (special mode) 12 7.5 arc min (10 radius) 5 arc min. (10 radius) 5500 1º 30 1000 15000 2x105$cm^2s^1$ 3x105 to 3x106 0.1 Crab- transient Continuum ~ 3x105cm 2s -1 5x105 $cro^2s^1$ 5x108$cm^2s^1$ 6x10■erG $cm^2$-burst Weight (Kg) 1730 Average Power (watts) Height (m) x Width (m) Bit Rate (kbps) 140 1.5x(1.5x2.3) 1477 195 2.8x1.7 1708 570 170 100 2.25x1.65 0.7x0.6x0.7 6.0 4.5 5.0 1.5

698 NASA AND PLANETARY EXPLORATION Document III-33 Document title: Astronomy Survey Committee, National Research Council, “Astronomy and Astrophysics for the 1980s,” January 1982. Source: National Academy of Sciences, Washington, D.C. The U.S. astronomical community, under the auspices of the National Research Council of the National Academy of Sciences, each decade prepared a blueprint for what it hoped would happen in astronomy and astrophysics in the coming ten years. This is the third in the series of these "decadal" reports. It was pre pared by a committee chaired by Harvard astronomer George Field, and became known as the Field report. Of special note is the high priority the report assigns to space-based astronomical investigations. [cover] Astronomy and Astrophysics for the 1980s VOLUME 1: Report of the Astronomy Survey Committee Astronomy Survey Committee Assembly of Mathematical and Physical Sciences National Research Council NATIONAL ACADEMY PRESS Washington, D.C. 1982 ******** [ix] Astronomy Survey Committee GEORGE B. FIELD, Harvard-Smithsonian Center for Astrophysics, Chairman MICHAEL J. S. BELTON, Kitt Peak National Observatory E. MARGARET BURBIDGE, University of California, San Diego GEORGE W. CLARK, Massachusetts Institute of Technology S. M. FABER, University of California, Santa Cruz CARL E. FICHTEL, NASA Goddard Space Flight Center ROBERT D. GEHRZ, University of Wyoming EDWARD J. GROTH, Princeton University JAMES E. GUNN, Princeton University DAVID HEESCHEN, National Radio Astronomy Observatory RICHARD C. HENRY, The Johns Hopkins University RICHARD A. MCCRAY, Joint Institute for Laboratory Astrophysics and the University of Colorado

EXPLORING THE UNKNOWN 699 JEREMIAH OSTRIKER, Princeton University EUGENE N. PARKER, University of Chicago MAARTEN SCHMIDT, California Institute of Technology HARLAN J. SMITH, University of Texas, Austin STEPHEN E. STROM, Kitt Peak National Observatory (ex officio) PATRICK THADDEUS, NASA Goddard Institute for Space Studies and Columbia University CHARLES H. TOWNES, University of California, Berkeley ARTHUR B. C. WALKER, Stanford University E. JOSEPH WAMPLER, University of California, Santa Cruz PAUL BLANCHARD, Executive Secretary DALE Z. RINKEL, Administrative Secretary ******** [13] 2- RECOMMENDED PRIORITIES FOR ASTRONOMY AND ASTROPHYSICS IN THE 1980s The Astronomy Survey Committee takes note at the outset of the support provided to U.S. astronomy and astrophysics over the past decades through the scientific programs of the National Science Foundation (NSF), the National Aeronautics and Space Administra- tion (NASA), and other federal agencies. This support has enabled U.S. astronomical research to maintain an overall position of world leadership and has vastly widened our horizons for exploration of the Universe. The programs recommended in this report have been selected from research activi- ties that were, at the beginning of the Survey, candidates for implementation in fiscal year 1983 and beyond. Before presenting a summary of its recommendations, however, the Committee wishes to emphasize the importance of approved, continuing, and previously recommended programs to the progress of astronomical research during the remainder of the decade. The present Committee's recommendations take explicit account of such programs and build upon them. The Committee calls particular attention to the need for support of the following approved and continuing programs, for which the order of listing carries no implication of priority: Space Telescope and the associated Space Telescope Science Institute; second- generation Space Telescope instrumentation; the Gamma Ray Observatory; NASA level-of- effort observational programs, including research with balloons, aircraft, and sounding rockets, together with the [14] Explorer and Spacelab programs; the Solar Optical Telescope and the Shuttle Infrared Telescope Facility for Spacelab; facilities for the detec- tion of neutrinos from the solar interior; federal grants in support of basic astronomical research at U.S. universities; and programs at the National Astronomy Centers. The 25- Meter Millimeter-Wave Radio Telescope, which was recommended in an earlier form in the Greenstein report, has not yet been implemented. The present status of these approved, continuing, and previously recommended programs is described later in this chapter; their importance for the health of U.S. astronomy in the 1980s is discussed in Chapter 4. [not included]

 SUMMARY OF THE RECOMMENDED PROGRAM The Astronomy Survey Committee recommendations for a program in astronomy and astrophysics for the 1980s fall into three general categories: • Prerequisites for new research initiatives; New programs; and Programs for study and development. As noted in the Preface, the observational components of these recommendations are restricted to remote sensing from the Earth or its vicinity. A background and overview of the recommendations follows later in this chapter. Prerequisites for New Research Initiatives In order to be effective, the recommended new research initiatives for the coming decade must be supported by a set of Prerequisites that apply to both the gathering and the analysis of the data produced. These Prerequisites are essential for the success of major programs but are inexpensive by comparison. Although significant support already exists for each, the Committee strongly recommends substantial augmentations in the fol- lowing areas, in which the order of listing carries no implication of priority: A. Instrumentation and detectors, to utilize the latest technology to enhance the effi- ciency of both new and existing telescopes in the most cost-effective manner; B. Theory and data analysis, to facilitate the rapid analysis and understanding of observational data; [15] C. Computational facilities, to promote data reduction, image processing, and theo- retical calculations; D. Laboratory astrophysics, to furnish the atomic, molecular, and nuclear data essential to the interpretation of nearly all astronomical observations; and E. Technical support at ground-based observatories, to ensure that modern astronomi- cal instrumentation is maintained in the best condition permitted by the state of the art. A detailed consideration and justification of these Research Prerequisites appears in Chapter 5. [not included] New Programs The Astronomy Survey Committee recommends the approval and funding of new programs in astronomy and astrophysics for the 1980s. These have been arranged into three categories according to the scale of resources required. A. Major New Programs The Committee believes that four major programs are critically important for the rapid and effective progress of astronomical research in the 1980s and is unanimous in recommending the following order of priority: 1. An Advanced X-Ray Astrophysics Facility (AXAF) operated as a permanent national observatory in space, to provide x-ray pictures of the Universe comparable in depth and detail with those of the most advanced optical and radio telescopes. Continuing the remarkable development of x-ray technology applied to astrono- my during the 1970s, this facility will combine greatly improved angular and spec-

EXPLORING THE UNKNOWN 701 tral resolution with a sensitivity up to one hundred times greater than that of any previous x-ray mission. 2. A Very-Long-Baseline (VLB) Array of radio telescopes designed to produce radio images with an angular resolution of 0.3 milliarcsecond. Among many potential applications of profound importance, this instrument will probe the small-scale structure surrounding the enigmatic energy sources in the cores of quasars and active galactic nuclei and will directly determine the distance scale within our Galaxy with unprecedented accuracy. 3. A New Technology Telescope (NTT) of the 15-m class operating from the ground at wavelengths of 0.3 to 20 µm, to provide a tenfold increase in light-gathering capacity at visual wavelengths [16] and a hundredfold increase in speed for spec- troscopy at infrared wavelengths, with application to a very wide range of scien- tific problems. The Committee finds the scientific merit of this instrument to be as high as that of any other facility considered and emphasizes that its priority ranking does not reflect its scientific importance but rather its state of techno- logical readiness. The design studies needed before NTT can be constructed are of the highest priority and should be undertaken immediately. 4. A Large Deployable Reflector in space, to carry out spectroscopic and imaging obser- vations in the far-infrared and submillimeter wavelength regions of the spectrum that are inaccessible to study from the ground, thus extending the powerful capa- bilities of NTT to these longer wavelengths. Such an instrument, in the 10-m class, will present unprecedented opportunities for studying molecular and atomic processes that accompany the formation of stars and planetary systems. B. Moderate New Programs In rough order of priority, these are: 1. An augmentation to the NASA Explorer program, which remains a flexible and high- ly cost-effective means to pursue important new space-science opportunities covering a wide range of objects and nearly every region of the electromagnet- ic spectrum. 2. A far-ultraviolet spectrograph in space, to carry out a thorough study of the 900-1200- Å region of the spectrum, important for studies of stellar evolution, the interstel- lar medium, and planetary atmospheres. 4. 3. A space VLB interferometry antenna in low-Earth orbit, to extend the powerful VLBI technique into space in parallel with the rapid completion of a ground-based VLB Array, in order to provide more detailed radio maps of complex sources, greater sky coverage, and higher time resolution than the Array can provide alone. The construction of optical/infrared telescopes in the 2-5-m class, to observe transient phenomena, conduct long-term survey and surveillance programs, provide cru- cially needed ground-based support to space astronomy, and permit the develop- ment of instrumentation under realistic observing conditions. The Committee particularly encourages federal assistance for those projects that will also receive significant nonfederal funding for construction and operation. [17] 5. An Advanced Solar Observatory in space, to provide observations of our Sun-the nearest star-simultaneously at optical, extreme ultraviolet, gamma-ray, and x-ray wavelengths, to carry out long-term studies of large-scale circulation, internal dynamics, high-energy transient phenomena, and coronal evolution.

702 NASA AND PLANETARY EXPLORATION 6. A series of cosmic-ray experiments in space, to promote the study of solar and stellar activity, the interstellar medium, the origin of the elements, and violent solar and cosmic processes. 7. An astronomical Search for Extraterrestrial Intelligence (SETI), supported at a modest level, undertaken as a long-term effort rather than as a short-term project, and open to the participation of the general scientific community. C. Small New Programs The program of highest priority is: An antenna approximately 10 m in diameter for submillimeter-wave observations, at an excellent ground-based site. Other programs of outstanding scientific merit, in which the order of listing carries no implication of priority, are as follows: • • A spatial interferometer for observations of high angular resolution in the mid- infrared region of the spectrum; A program of high-precision optical astrometry; and A temporary program to maintain scientific expertise at U.S. universities during the 1980s through a series of competitive awards to young astronomers. Detailed discussion and justification of the New Programs appears in Chapter 6. [not included] Programs for Study and Development Planning and development are often time-consuming, especially for large projects. It is therefore important during the coming decade to begin study and development of pro- grams that appear to have exceptional promise for the 1990s and beyond. Projects and study areas recommended by the Committee in this category include the following, in which the order of listing carries no implication of priority: A. Future x-ray observatories in space; B. Instruments for the detection of gravitational waves from astronomical objects; [18]C. Long-duration spaceflights of infrared telescopes cooled to cryogenic tempera- tures; D. A very large telescope in space for optical, ultraviolet, and near-infrared observa- tions; E. A program of advanced interferometry in the radio, infrared, and optical spectral regions; F. Advanced gamma-ray experiments; and G. Astronomical observatories on the Moon. Detailed discussion of the Programs for Study and Development appears in Chapter 7. [not included]

EXPLORING THE UNKNOWN 703 Document III-34 Document title: "The Great Observatories for Space Astrophysics," NASA Astrophysics Division, 1984. Source: Charles Pellerin, personal collection. By the mid-1980s, NASA had plans in place for four major space-based astronomical facilities to explore the infrared, optical, x-ray, and gamma-ray wavelengths: the Space Infrared Telescope Facility, the Hubble Space Telescope, the Advanced X-ray Astrophysics Facility, and the Gamma Ray Observatory. Constraints on NASA's space science budget during that time, however, led astronomers to debate which of these missions should have priority. Charles Pellerin, then Director of Astrophysics at NASA, believed that the astronomy community should take a different course, pushing not for one or two missions but for all four missions, because data in all of these wavelengths were necessary to provide the most information about the universe. Needing a way to explain clearly the importance of funding all four of these observatories to Congress and the public, Pellerin and other astronomers developed an illustrated brochure explaining the four missions and their objectives. Impressed with Pellerin's packaging of the astronomy missions, George Field, leader of the National Research Council's study of astronomy and astrophysics in the 1980s, dubbed the four spacecraft the "Great Observatories." As the title of the original "comic book" and this second printing of the document sug- gest, the name stuck. Taken to the Office of Management and Budget as well as to various congres- sional offices by astronomers, the booklet's message and easy-to-understand language and graphics were a major influence in securing funding for all four Great Observatories. [cover sheet] THE GREAT OBSERVATORIES FOR SPACE ASTROPHYSICS

704 NASA AND PLANETARY EXPLORATION [1] NASA THE GREAT OBSERVATORIES FOR SPACE ASTROPHYSICS The origin of the Universe The fundamental laws of physics The birth of stars, planets and life National Aeronautics and Space Administration Astrophysics Division [2] An Astronomical Heritage Although astronomy is a science that has been practiced since ancient times, the Universe remains veiled in mystery. The ruins of Stonehenge and Chichen Itza, the clay tablets of Babylon, the cosmic models of Greek schools of thought, and the celestial mythologies of various cultures offer historical evidence for widespread astronomical observations. Until Galileo revolutionized astronomy with the telescope, however, our understanding of the Universe owed more to preconceptions than to precise observations and measurements. Since Galileo first peered into the heavens with a device more sensi- tive than the human eye, telescopes and observatories have proliferated, revealing a rich- ly varied Universe. Astronomers study the nature of the Universe by observing its contents and behavior, while astrophysicists seek to understand these observations in terms of consistent laws of physics. Limited for centuries to observations in the visible band of the electromagnetic spectrum, scientists now have access to the Universe at virtually all wavelengths. The tremendous advance that has occurred in our lifetimes became possible with spaceflight: Placing sensitive astronomical instruments above the filtering atmosphere opened new windows onto the cosmos and revealed intriguing objects and events there. Today we are still motivated by the ancient urge to observe, measure, compute, and thereby come to greater understanding of the nature of the Universe. We have at our dis- posal the most advanced technology, and we have new opportunities to place entire obser- vatories into space for investigations across the spectrum. Our astronomical heritage flourishes on the insights and discoveries of this new Era of Space Observatories.

[3] EXPLORING THE UNKNOWN 705 ASTRONOMY TIMELESS EXPLORATION OF THE UNIVERSE, [4] The Popular Appeal of Astronomy Astronomy is in the midst of its most exciting period since Galileo probed the heav- ens with the first telescope. Widespread public interest is evident in the flowering of ama- teur astronomy societies, the popularity of space science and astronomy publications, and the attendance figures for astronomy lectures, films, museum exhibits, and plane- tarium shows. In the United States today, there are at least a quarter million amateur astronomers, many of them children who will become the scientists and engineers of tomorrow. The National Air and Space Museum, the country's principal museum dedicated to space exhibits, has attracted up to 15 million visitors annually, and attendance continues to grow. More than 350,000 visitors a year pay admission to attend the planetarium shows there. A thousand other planetaria exist around the country, most of them in high schools, where their educational value is especially significant. Audiences for astronomy lectures and films are typically large and enthusiastic. Television productions based on astronomy are extraordinarily popular, attracting millions of viewers. Many of the mass-circulation magazines (including Time, Newsweek, National Geographic, Smithsonian, Omni, Scientific American, Discover, and others) vividly report astronomical discoveries to millions of readers.

706 NASA AND PLANETARY EXPLORATION The popular appeal of astronomy, for education and entertainment, is enormous. Almost everyone is curious about the Universe. [5] EVER ALMOST EVERYONE IS CURIOUS ABOUT THE UNIVERSE. PLANETARIA ADMI ONE onnul COSMOS TELEVISION SPECIALS ANERN POPULAR PUBLICATIONS AMATEUR ASTRONOMERS [6] Careers in Astronomy An education in astronomy and space science can lead to a variety of careers. Some graduates apply their skills to the design of new techniques for observing and interpreting cosmic processes at great distances across the Universe. Others study our more immediate environment within the solar system, in part to determine causes of climatic variations. Still others become teachers or put their talents to use in industry and government. Research: Scientists extend the frontiers of knowledge in the various disciplines of astronomy and astrophysics by observation, analysis, and theory. They find employment in universi- ties, observatories, and government centers. Teaching: The study of the Universe is impor- tant, and popular, in the curriculum at all levels: General science in elementary and secondary schools * * Basic astronomy in colleges and universities * Graduate and postgraduate courses at dozens of universities.

EXPLORING THE UNKNOWN 707 Industry: Many people interested in astronomy join industry to conduct applied research in optics, electronics, and computer science. Others become involved in instrument design and fabrication. These scientists and engineers are responsible for the advanced technol- ogy that makes further discovery possible. NASA: Astronomers provide leadership for the nation's space program, managing the pio- neering exploration of space and meeting the challenges of tomorrow. [7] EDUCATION &.CAREERS. SCIENTISTS AND ENGINEERS OF THE FUTURE STRONOMY TEACHING RESEARCH NASA INDUSTRY [8] Astronomy and Technology: A Continuing Exchange of Novel Ideas Over the centuries, astronomy and technology have progressed hand in hand. The study of the Universe has benefited from improved observational devices and techniques. By the same token, developments in astronomy have led to practical applications in other disciplines. 1500-1600 * Increasingly accurate maps of the sky for navigation 1600-1700 * Christian Huygen's invention of the pendulum clock for navigational time keeping

708 NASA AND PLANETARY EXPLORATION * Newton's development of the calculus, the laws of motion and the law of universal grav- itation as a means to explain the motions of planets and comets 1800-1900 * Increasingly sophisticated optical innovations by astronomers (William Herschel, Fraunhofer, Lord Rosse, Alvan Clark, and many others) * Development of increasingly sensitive photographic techniques * Lockyer's discovery of a new chemical element, helium, on the sun before it was known on Earth 1900-NOW * Hans Bethe's theoretical prediction of hydrogen fusion at the center of the sun, a pre- cursor for all modern fusion efforts * Lyman Spitzer's development of astrophysical plasma theory, the basis of present devices for releasing energy from controlled fusion * Very long baseline radio astronomy techniques used in high-precision geodesy to survey the structure of the Earth * Techniques of celestial mechanics, precursors to the development of accurate spacecraft navigation. The mutually beneficial interaction between astrophysics and technology continues today. [9] ASTRONOMY AND TECHNOLOGY AND GEOORRY YEARS: 1500 1800 1900 2000

EXPLORING THE UNKNOWN 709 [10] Observing the Universe with Improved Sensitivity Over the past two decades, NASA has introduced increasingly sensitive instruments into space. In astronomy, families of telescopes have been developed and placed in orbit for observations across the entire electromagnetic spectrum, especially those parts blocked by the atmosphere. Each successive telescope has extended the limits of sensitivity and provided greater insight into the structure of stars, galaxies, and the cosmos. For these successes, new tech- nologies had to be created and exploited. Members of the new generation of space observatories offer significant new gains in sensitivity through state-of-the-art technology. * The GAMMA RAY OBSERVATORY (GRO) will explore the most energetic part of the spectrum across a much greater wavelength range than its predecessors. * The ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF) will cover the X-ray por- tion of the spectrum with a hundred-fold improvement in sensitivity. * The HUBBLE SPACE TELESCOPE (HST) will penetrate deep into the Universe in vis- ible and ultraviolet light, expanding the volume of observable space several hundred times. * The SPACE INFRARED TELESCOPE FACILITY (SIRTF) will span the infrared part of the spectrum with a thousand-fold increase in sensitivity. To complement these sensitive space telescopes, the astronomical community is cur- rently considering two powerful new ground-based observatories: the Very Long Baseline Array (VLBA), an intercontinental network of radio telescopes, and the National New Technology Telescope (NNTT), a large optical telescope. In addition, NASA's Solar Optical Telescope (SOT) will provide detailed data on our nearest star, the sun, to aug- ment our studies of distant stars and cosmic processes. With these new observatories, we will be able to open more of the Universe to scrutiny, to look back in time and space for order and meaning.

RELATIVE SENSITIVITY 710 [11] 10 10 10 NASA AND PLANETARY EXPLORATION SENSITIVITY OF IMAGING ASTRONOMICAL INSTRUMENTS HEADS UHURU 10 10 SAMMA RA GALILEOS TELESCOPE THE EVE INFRARED VLA [12] Technology for the Future Astronomical observations pose some of the greatest challenges to modern technolo- gy. Engineering difficulties overcome by astrophysicists often provide solutions to more general technical problems. We expect new technologies developed for the four space observatories to stimulate future applications in space and on Earth. * GRO introduces a propulsion system that can be refueled in orbit to extend the lifetime of the observatory. * AXAF's nested grazing-incidence mirrors will provide the most advanced X-ray focussing optics presently known. Previous X-ray astronomical advances have already led to com- mercial applications in low-dosage imaging systems. * HST has already pioneered the construction of higher precision optics than any ever built. Its spacecraft pointing control will cross new thresholds of accuracy. * SIRTF will provide longer endurance for ultra-low-temperature apparatus in space, a requirement for many other high-precision technologies. Previous infrared astronom- ical missions pioneered the handling of liquid helium, the ultimate refrigerant, in space. However, SIRTF introduces the new capability of replenishing liquid helium coolant in orbit.

EXPLORING THE UNKNOWN 711 These advanced technologies will be of benefit not only for scientific research but also for practical down-to-Earth uses. We can only guess what new applications will result from the spread of these technologies into everyday life. [13] AXAF GRAZING INCIDENCE OPTICS NESTED ARRAY X-RAY ENERGY OF HYPERBOLDID Focus. SUN SHA-E MULTILAYER INSULATION SUPERFLIND. HELUM TANK SECONDARY MEROG MIRROR MULTIFLS INSTRUMEN! CHAMBER NESTED ARRAY OF PARABOLOIDS SIRTE SUPERCOOLED OPTICS [14] Discovering the Nature of the Universe Astronomical discoveries have been occurring at a quickening pace since the devel- opment of the first telescope, and particularly in the past few decades. These discoveries are closely linked to the introduction of new technologies into the field. The discovery of X-ray stars and X-ray galaxies in the 1960's was made possible by the flight of first-generation X-ray telescopes on some of the early rockets. Infrared stars and galaxies were discovered about the same time with novel detectors that had just become available. The listed discoveries, though impressive, are only a fraction of those remaining to be made. New technologies in the era of space observatories will certainly lead to further dis- coveries just as striking as those of the past. What might these be? Possibly black holes at the distances of the nearest stars, having masses similar to those of ordinary stars and detected through the X-ray emission pro- duced as the black hole gravitationally accretes interstellar matter. Or perhaps an infrared

712 NASA AND PLANETARY EXPLORATION planet orbiting a nearby star with a period identical to that of some unusual radio signals from the same part of the sky, suggesting the existence of an intelligent, technically advanced civilization. Or else bizarre “shadow galaxies" or networks of massive cosmic "strings," predicted by some of our Grand Unified Theories of elementary particle physics but never seen in the laboratory. These particles, produced only at the enormous energies prevalent in the early exploding Universe, would be revealed through the X-ray emission from hot gas gravitationally attracted to them. Discoveries: 1. Stars 2. Planets 3. Novae 4. Comets 5. Moons 6. Rings 7. Galactic Clusters 8. Clusters of Galaxies 9. Interplanetary Matter 10. Asteroids 11. Multiple Stars 12. Variable Stars with Nebulosity 13. Planetary Nebulae 14. Globular Clusters 15. Ionized Gas Clouds 16. Cold Interstellar Gas 17. Giants/Main Sequence Stars 18. Cosmic Rays 19. Pulsating Variables 20. White Dwarfs 21. Galaxies 22. Cosmic Expansion 23. Interstellar Dust 24. Novae/Supernovae 25. Galaxies With/Without Gas 26. Supernova Remnants 27. Radio Galaxies 28. Magnetic Variables 29. Flare Stars 30. Interstellar Magnetic Fields 31. X-Ray Stars 32. X-Ray Background 33. Quasars 34. Microwave Background 35. Masers 36. Infrared Stars 37. X-Ray Galaxies 38. Pulsars 39. Gamma-Ray Background 40. Infrared Galaxies 41. Superluminal Sources 42. Gamma-Ray Bursts 43. Unidentified Radio Sources

[15] CONVUCATIVE NUMBER OF DISCOVERIES YEARS: [16] EXPLORING THE UNKNOWN 713 THE INCREASING PACE OF DISCOVERY FLANE NOWAL JUPITERS ■■■■ NEBULA GAMMA RAY. |QUASADS] COSMIC EXPANSION COMED 000 ■1600 1650 1700 1500 1900 950 NASA's major contribution to modern astrophysics has been the agency's ability to place powerful new telescopes into orbit. From their vantage point in space, these obser- vatories can sense gamma rays, X-rays, and ultraviolet, optical, and infrared radiation undisturbed by the distorting, absorbing atmosphere. Discoveries of ultra-hot gas in clusters of galaxies, gamma background-radiation from the Universe, and galaxies which emit virtually all their energy in the infrared have all resulted from this capability. Observations in each wavelength band reveal a new Universe.

714 [17] NASA AND PLANETARY EXPLORATION OBSERVATORIES IN SPACE, HIGH ABOVE THE EARTH'S ABSORBING ATMOSPHERE, PROVIDE NEW VISTAS ON THE UNIVERSE. NASA HAS LONG BEEN THE LEADING ARCHITECT OF SPACE OBSERVATORIES.... SATELLITES BALLOONS AIRPLANES MOUNTAIN-TOP DESERVATORTES SEA LEVEL GAMMA BAYS QV. VISIBLE INFRARED RADIO. [18] The Milky Way Our galaxy, the Milky Way, is populated by star clusters, dusty clouds of turbulent gas, exploding or collapsing stellar masses, and gradually evolving systems of stars - phenome- na that are revealed by observations at widely differing wavelengths. Through the use of powerful telescopes, we hope to observe and comprehend these processes that reflect the birth of stars, their eventful lives, and their ultimate death. * At radio wavelengths we detect cool clouds in space; some are destined to contract to form new stars, while others are ejected at high speeds, emitting radio waves characteris- tic of water vapor masers. * At infrared wavelengths we probe clouds warmed by stars that have formed within them; we also register dying stars throwing off shells of matter. * At visible wavelengths we see millions of stars like our sun, and we can study their evo- lution as they consume their nuclear energy. * At ultraviolet wavelengths we detect the hottest stars. Some are still actively consuming nuclear energy; others, like white dwarfs, are dying remnants of small stars which once were active. * At X-ray wavelengths we see matter at ultra-high temperatures falling on neutron stars■ the remains of more massive dead stars.

* At gamma-ray wavelengths we detect sudden bursts of intense emission from sources not yet understood. By combining these different pictures of our galaxy, we gain greater understanding, while any one of these observations alone would leave us puzzled. [19] INTENSELY HOT AND EXTREMELY COLD COSMIC MATTER RADIATE AT WIDELY DIFFERING WAVELENGTHS. GAMMA BURSTS X-RAY PULSARS. HOT STARS: WARM DUST COLD GAS, MASERS OBSERVATORIES TUNED TO EACH WAVELENGTH BAND WILL REVEAL A COMPLETE PICTURE. ■■■■ GRO 10,000,000 HST. SIRTF VLBA TEMPERATURE SCALE GAMMA RAYS X-RAYS LIVE INFRARED MICROWAVE RADIO MSIBLE LIGHT [20] A Typical Cluster of Galaxies The gamma ray emission from clusters of galaxies is expected to emanate primarily from quasars and from the nuclei of active galaxies. With the next generation observato- ry, GRO, we will be able to determine whether most of the known gamma radiation arriv- ing from the Universe originates in quasars, or whether there are other powerful, but presently unknown, sources of gamma ray emission. The X-ray map of a cluster frequently is dominated by a hot, diffuse plasma permeat- ing intergalactic space. Quasars also show up on such a map, while individual galaxies appear much fainter. Pictures recorded at visible wavelengths show starlight from all the members of a clus- ter of galaxies. Infrared radiation predominantly comes from dusty galaxies in which dust grains absorb virtually all the starlight and re-emit this energy at longer wavelengths.

716 NASA AND PLANETARY EXPLORATION The radio view is dominated by the luminous core of a massive central galaxy, from which magnetically channeled jets of electrons and protons are ejected at nearly the speed of light. [21] CLUSTERS OF GALAXIES PROVIDE AN- EVEN GREATER CONTRAST IN APPEARANCE. GAMMA RAYS X-RAYS MSIBLE INFRARED RADIO QUASARS HOT PLASMA STARS IN GALAXIES HEATER ENERGETIC PUST ELECTRONS 4PROTONS ARE FURTHER CHANNELS OF INVESTIGATION LIKELY TO REVEAL STILL GREATER COMPLEXITIES? [22] What If We Could Observe in Just One or Two Wavelength Bands? Many discoveries become apparent only through a combination of observations. For example, quasars, discovered in 1963 by virtue of their powerful radio emission, had been recorded on photographic plates for many decades. Nobody had noticed them because they looked so much like normal stars. Later, more extensive optical data showed quasars to lie far out in the Universe. Recent observations with NASA's HEAO-2 (Einstein) observatory have shown quasars to be even more powerful emitters of X-rays than of radio or light waves. To understand the nature of quasars and many other celestial objects, we need to study them at all wavelengths.

[23] AXAF HST EXPLORING THE UNKNOWN 717 WHAT IF WE COULD SEE ONLY ONE OR TWO COLORS OR WAVELENGTHS? MISLUNGAY Doe WE MIGHT MISS, A SIRTF [24] Fundamental Questions in Astrophysics Our thoughts about the long-term future of the human race involve fundamental questions about the nature of the cosmos - its past and its future, its governing physical laws, its harsh explosions, and its potential for hospitable planetary systems. We ask: * How did the Universe form and evolve in the first few seconds? Can we learn more about the basic laws of physics from the effects they have had on the structure of the Universe? * How did galaxies and clusters of galaxies initially form and how have they evolved? * Will we need new laws of physics to describe observed phenomena? Will the Law of Gravitation have to be modified or will new fundamental particles be found to play a central role? * Can massive stars or galaxy-size aggregates collapse to form black holes, liberating enormous amounts of energy? Are such black holes the energy sources of quasars and active galactic nuclei? How do these powerful sources affect the galaxies in which they reside? * How do stars and star clusters form and die, and how do they interact with interstellar matter? Do shock waves from stars dying in supernova explosions induce star formation? How do magnetic fields arise in interstellar matter and in stars? * How are planetary systems formed? How many stars have planets and how many might

 be habitable? Where and how did life start? Are there intelligent civilizations elsewhere in the Universe? [25] FUNDAMENTAL QUESTIONS: HOW DID THE UNIVERSE BEGIN? HOW DID GALAXIES FORM PLANETS FORMED HOW DID LIFE START WILL WE FIND NEW LA OF FRIENDS TH■T HOW ARE STARS BORN HOW DO STARS DIE DO BLÁLÉ HOLES EXIST [26] Birth Places of Stars We know that stars must be forming in our galaxy today. Although the Milky Way is more than ten billion years old, we see stars that are thousands of times younger. A star can continue to shine only as long as it has a supply of energy to radiate away into space. The most luminous stars quickly exhaust these limited supplies and must be young, no older than a few million years. Young stars are always found near dark, dusty gas clouds, the birth places of stars. The gaseous central portions of a cloud contract, becoming ever more compact until a star is born. The early collapse of a contracting core can be detected only with infrared and radio observations that penetrate the dust--shrouded regions. SIRTF and radio tele- scopes have this capability. Once a young star is formed and its cocoon of dust is blown away by powerful stellar winds, eruptive magnetic processes that mark the final stages of star formation can be studied with sensitive optical telescopes such as HST. Similar magnetic phenomena occur, on a smaller scale, on the surface of the sun, our best laboratory for studying these violent outbursts. The Solar Optical Telescope (SOT) will be a powerful tool not only for investigations of the sun but also for insight into the

EXPLORING THE UNKNOWN 719 storage of magnetic energy at the surfaces of young stars. This energy is later unleashed sporadically in enormous flares. [27] OUR SUN IS ONE OF COUNTLESS STARS. ARE STARS FORMING EVEN NOW IN INTERSTELLAR CLOUDS? YOUNG HST VLBA SIRTE [28] Life Cycles of Stars The birth of stars may well be triggered by the explosion of a supernova that com- presses a nearby dusty cloud of gas, which then collapses to form a new group of stars. Some of these are more massive than others and begin to shine thousands of times more brightly than the sun. Such stars consume their supply of nuclear fuel in a few million years and collapse to form a neutron star, or possibly a black hole. In this collapse, enor- mous amounts of energy are suddenly liberated, and the outer shell of the star is hurled into space in another supernova explosion. X-ray observations of the remains of such explosions can tell us much about the original star as well as the exploding shell. Less massive stars, like our sun, never explode as supernovae. Instead, they shine steadily, at a far more subdued rate, for ten billion years before continuing their lives, briefly as red giant stars and finally as faint white dwarfs. Some of these stars may originally be enveloped by a disk from which a system of planets settles out. Currently we have no way of knowing how many stars are orbited by planets or how many stars are encircled by disks. We hope to answer these questions by making optical observations with HST and infrared observations with SIRTF.

720 [29] NASA AND PLANETARY EXPLORATION WHAT IS THE LIFE CYCLE OF STARS? DO STARS FORM BECAUSE STELLAR EXPLOSIONS (SUPERNOVAE) COMPRESS NEIGHBORING GAS SLOUDS? MASSIVE STAR PRE-STEELAR COLLAPSE SUPERNOVA PLANETARY -SYSTEM AXAF BLACK ■■■■ [30] Quasars Quasars are distant, massive bodies so luminous that they outshine surrounding galax- ies a hundred times. We do not know how to explain this immense power. One possible model of a quasar consists of an intensely hot central source emitting gamma rays and embedded in X-ray-emitting plasma. Enveloping dust clouds absorb much of the emitted energy, re-radiating it at far-infrared wavelengths. An outermost, unobscured layer also radiates at ultraviolet and visible wavelengths. Plasma beams ejected from the central source at nearly the speed of light power distant radio lobes. How can so much energy be radiated from so compact a source? How can we account for the rapid variations in luminosity, from one month to the next, sometimes even from one hour to the next? Are quasars powered by a rapid succession of supernova outbursts in a central core, or is it more likely that matter falling onto a single, central black hole supplies all the energy? To clear up many of these questions, we need the full complement of our most pow- erful observatories, often working together to trace outbursts as they evolve -sometimes emitting successively in different wavelength bands, sometimes simultaneously varying across the entire spectrum.

EXPLORING THE UNKNOWN 721 These detailed observations should clarify the nature of the central engines powering quasars and explain the structure of ambient regions. [30] QUASARS ARE THE MOST POWERFUL KNOWN ENERGY SOURCES IN THE UNIVERSE. HOW DO THEY GENERATE SO MUCH ENERGY? AXAE NNTT VLBA QUASAR SIRTF [32] Black Holes Black holes are enormously compact bodies, so dense that matter falls into them under an irresistible gravitational pull. So far we are not sure whether nature produces such holes. If they do exist, black holes could be very massive, or quite small, or just about as massive as a star. The largest black holes might be the power sources for quasars; each could have a mass comparable to that of an entire galaxy of a hundred billion stars. The smallest black holes could have masses of only a billion tons - roughly the mass of the Rock of Gibraltar - and could be capable of exploding at any time, annihilating them- selves totally in an enormous flash of gamma radiation lasting no more than a few seconds. A stellar-sized black hole could have a mass five or ten times greater than the sun's. Such a black hole in a binary system with a giant star could syphon [sic] matter off the giant's surface, giving rise to X-ray emission as this matter crashed down onto an accretion disk encircling the black hole.

722 NASA AND PLANETARY EXPLORATION A different stellar-sized black hole, also a member of a binary system but sufficiently distant from its companion star to leave it intact, might be detected through careful obser- vations of the companion's orbital motion. The companion would appear to be circling a massive center, but there would be no radiation coming from that point; it would seem as though nothing were there except a strong gravitational pull, a black hole. We are not yet sure that we have observed any one of these, but we know of likely can- didates that need to be studied with the most powerful observatories we can build. [33] WHAT ARE BLACK HOLES? DO THEY REALLY EXIST? BLACK HOLES MAY EXIST WITH DIFFERENT MASSES AND DIFFERENT SIGNATURES: BINARY MOTION AROUND INVISIBLE COMPANION GAMMA BUESTS, INFALLING MATTER FROM BIMARY COMPANION QUASAR NUCLEI [34] Magnetic Energy Storage Magnetic fields on the surface of the sun, in inter-planetary space, in far-reaching stellar jets, in interstellar clouds, in the spiral arms of galaxies, and in the giant inter- galactic jets spanning an entire cluster of galaxies - are able to store enormous amounts of energy. Sometimes the stored energy is released in an explosive flare, through processes we do not understand at all. In fact, we have no convincing theories to explain the gen- eration and existence of such strong magnetic fields. To gain greater understanding, we must not only look beyond the solar system but also observe more carefully within it, looking at magnetic processes occurring in the inter-

EXPLORING THE UNKNOWN 723 planetary medium and magnetic events taking place on the sun's surface. The Solar Optical Telescope (SOT) will help us to understand solar magnetic events, interplanetary probes will help us to understand transformations in the magnetized interplanetary plas- ma, and our other observatories should enable us to relate these local effects to phenom- ena taking place on galactic and intergalactic scales. [35] MAGNETIC FIELDS EXIST IN OBJECTS OF DIFFERENT SIZES THROUGHOUT THE UNIVERSE. WHAT ARE THEIR EFFECTS? •THIS IS A PROBLEM ON WHICH WE EXPECT TO MAKE PROGRESS NOT JUST THROUGH ·DIRECT COSMIC OBSERVATIONS, BUT ALSO BY USING SOLAR AND INTERPLANETARY DATA. STELLAR JETS-77 STARS AND THE SUN INTERPLANTAG GALAXIES 4-TONIZED AND MOLECULAR CLOUDS INTERGALACTIC FIELDS [36] Invisible Mass Most of the matter in the Universe is known to us only through the gravitational forces it exerts on stars, galaxies and other visible sources, whose orbital motions we can follow. We have no adequate explanation for this invisible mass, which has given rise to one of the most troubling questions in astrophysics: what is it? One suggestion is that most galaxies may have a faint halo of low-luminosity stars. These could be traced with an optical telescope like HST placed above the Earth's atmosphere and therefore capable of seeing fainter diffuse distributions of stars. The matter might also be dis- tributed in galactic halos in the form of brown dwarfs, bodies intermediate in mass, between Jupiter-sized objects and the least massive stars known to emit visible light. Brown dwarfs would emit primarily at infrared wavelengths and be observed with SIRTF A further possibility is a halo of black holes or of low-mass stars. In either case, a faint diffuse glow of X-rays would emanate from the halos of galaxies, a glow that AXAF would permit us to detect.

 An entirely different tracer of invisible mass in clusters of galaxies is intensely hot intergalactic plasma. X-ray emission from this plasma is brightest in the innermost por- tions of the cluster where most of the mass is concentrated. The distribution of X-ray brightness across the cluster provides us with a measure of total mass. Using this measure, AXAF would permit us to search for invisible mass in clusters at extreme distances across the Universe. Finally, families of new, exotic particles, like axions or gravitinos, or else networks of massive cosmic strings required by some elementary particle theories, could be responsi- ble for this invisible mass. Further study may permit us to distinguish among these differ- ent kinds of particles and provide insight into fundamental forces that govern their interactions. [37] 90% OF THE MATTER IN THE UNIVERSE VISIBLE. HOT INTERGALACTIC PLASMA IN DISTANT CLUSTERS. OF GALAXIES... WHAT IT? [38] Looking Out into the Universe Means Looking Back in Time The Universe is so large that even signals travelling at the greatest speed that can be attained - the speed of light - require billions of years to cross major portions of the tracts we can survey. This long delay in the arrival of radiation can work to our advantage. To understand how galaxies or quasars originated in a rapidly expanding Universe, we can look back in time to observe the contraction of protogalactic clouds, EXPLORING THE UNKNOWN 725 expected to emit far-infrared radiation, and young galaxies emitting radiation at visi- ble and infrared wavelengths. Young quasars should be powerful sources of X-rays as well as radio waves. These sources are beyond the range of present instruments, but those limits will be surpassed with the next generation of space observatories capable of surveying the sky out toward the moment when galaxies began to form, and beyond, to the impenetrable bar- rier that lies at a distance and time when electrons and protons were combining to form atoms of hydrogen. Currently, only radio telescopes can look back at that barrier from which the cosmic microwave background radiation emanates. Some day we may devise ways of looking even further back, but that may have to await the construction of gravita- tional wave detectors or neutrino observatories. [39] LOOKING BACK IN TIME TO'UNDERSTAND HOW QUASARS AND GALAXIES FORMED, WE NEED TO: LOOK FURTHER OUT INTO THE UNIVERSE TO OBSERVE EARLIER EPOCHS. OPAQUE BARRIER REGION OF INFERENCE *HOT PLASMA COOLING TO FORM ATOMIC *HYDROGEN PRESENTY LIMIT OBSERVABLE UNIVERSE PROTOGALANES FIRST 1 YEAR MILLION YEARS 20 BILLION YEARS (TOPAY) AGE OF THE EXPANDING N VLBA HIST GRO [40] What is the Geometry of the Universe? On Earth, distant objects appear small; their angular diameters diminish as they recede. In a curved, expanding Universe all that is changed. Distances across the Universe can be gauged by the extent to which radiation reach- ing us is shifted toward longer wavelengths -the extent to which it is red shifted. The more distant the emitting source, the greater is the red shift.

 In a closed Universe, the angular diameter of a galaxy or quasar observed at ever- increasing red shift - distance first shrinks but then expands. In an extreme open Universe, the angular diameter at first also declines but then slow- ly approaches a constant value at increasing red shift. With AXAF we will be able to locate the most distant quasars in the Universe, and with HST we will determine red shifts and diameters of the most distant galaxies and quasars to investigate whether our Universe is open and expanding forever, or closed and bound to collapse on itself billions of years from now. [41] WHAT IS THE GEOMETRY OF THE UNIVERSE? 15 IT CURVED ? 15. IT OPEN OR CLOSED? OPEN COSMOS CLOSED COSMOS INGREASING RED SHIFT. S [42] Matter and Antimatter in the Universe Much of the Universe we observe consists of hydrogen with an admixture of helium and heavier elements. However, everything we know about the Universe suggests that an equal amount of matter and antimatter - antihydrogen, antihelium and heavier antiele- ments should have existed at one time. We can search for traces of antimatter, because we know that matter and antimatter annihilate on contact. If there existed distant galaxies composed entirely of antimatter, we should be able to detect the gamma radiation emitted when gas ejected from such a galaxy encountered and annihilated ordinary matter from a galaxy like ours.

EXPLORING THE UNKNOWN 727 If substantial amounts of matter and antimatter existed at earlier epochs, before galaxies ever formed, remnants of this annihilation radiation might still persist, red shift- ed but observable at gamma-ray and X-ray wavelengths. [43] DID THE UNIVERSE ONCE CONTAIN EQUAL AMOUNTS OF MATTER (M) AND ANTIMATTER? COULD IT STILL? - WE NEED TO SEARCH FOR GAMMA AND X-RAY EVIDENCE FOR ANNIHILATION. Π WITH THE NEXT GENERATION OF COSMIC FAY INSTRUMENTS WE WILL ALSO. BE ABLE TO CONDUCT ANTIFROTON AND OTHER ANTIMATTER SEARCHES ww me www AXAF GRO [44] The Search for Other Planetary Systems Analysis of data from the Infrared Astronomical Satellite (IRAS) has shown disks of warm rocks and pebbles orbiting several stars. Such a protoplanetary disk might be a precursor of a planetary system or might co-exist with a system of planets like ours. By studying the planets of our own solar system, we should be able to gain increasing insight into how planets elsewhere might be formed and how we might best search for planets around other stars. Distant planets will be detected most readily through infrared radiation, since plan- ets are too cool to emit visible light, and stars are often less bright at infrared than at vis- ible wavelengths. A visible spectrum of a planetary system mainly will register stellar emission and reflect the chemical composition of the star. An infrared spectrum will show planetary contributions to the system's emission and could provide evidence for molecules, like methane, found on planets in our solar system but destroyed on the hot surface of a star like the sun.

728 NASA AND PLANETARY EXPLORATION SIRTF will be able to search for planets around the nearest stars. Spectra for any plan- ets detected could tell us the chemical composition of the atmosphere and help us deter- mine whether it might sustain life similar to that on Earth. Once planets are detected, a Search for Extraterrestrial Intelligence (SETI) would become more focused. [45] WE HAVE SOME EVIDENCE THAT PLANETS EXIST AROUND OTHER STARS. HOW COMMON ARE PLANETARY SYSTEMS IN OUR GALAXY C Wwebnych MINHABITED- SISTEM [46] Is Life on Earth Unique? The Earth is an insignificant companion of our sun, an unremarkable star: there are a thousand billion, billion stars just like the sun all over the Universe. Can we reasonably expect life to be unique here on Earth? There is no scientific basis on which that question can be answered today. However, the search for other planets may help us locate other solar systems in which we could pur- sue our quest for extraterrestrial life. Primitive life forms are likely to remain undetectable for a long time to come; but technologically advanced civilizations could be identified by artificial signals they generate. We know that stray television and FM broadcast signals radiated into space from Earth could be picked up by powerful radio observatories if they existed in the vicinity of near- by stars. Similarly, highly sensitive receivers on Earth might detect comparable signs of technological expertise around other stars in nearby parts of the Milky Way. The only

EXPLORING THE UNKNOWN 729 question that would then remain is how we could be sure that such signals were artificial rather than generated by some previously unidentified natural phenomenon. [48] IS INTELLIGENT LIFE COMMON ELSEWHERE IN THE UNIVERSE? • WE HAVE NO CLUES, BUT WE ARE SEARCHER UNUSUAL SIGNALS, DIFFERENT FROWNEDSE -EMITTED BY ASTROPHYSICAL OBJECTEER [48] Epilogue Astronomical searches have occupied human thought for millennia. Over the gener- ations, we have succeeded in gaining ever greater insight into the underlying forces at work in the cosmos. In the Space Station era, the family of permanent observatories in space will open the way to new, comprehensive studies of key remaining problems in astro- physics, helping us understand: * The birth of the Universe, its large-scale structure, and the formation of galaxies and clusters of galaxies; * The fundamental laws of physics governing cosmic processes and events; * The origin and evolution of stars, planetary systems, life and intelligence. If we succeed, we will leave a legacy to rank us with the great civilizations of the past.

730 NASA AND PLANETARY EXPLORATION [49] SPACE OBSERVATORIES PERMAN ESENCE [50] Prepared under the auspices of The NASA Astrophysics Division, Dr. Charles J. Pellerin, Jr., Director by Dr. Martin Harwit, Cornell University and Dr. Valerie Neal, Essex Corporation in consultation with the Astrophysics Management Operations Working Group Graphic design and illustration by Brien O'Brien Document III-35 Document title: Letter to Dr. L. J. Lanzerotti, Chairman, Space & Earth Science Advisory Committee, Bell Telephone Labs, from Glenn Mason, Associate Professor of Physics, University of Maryland, March 26, 1987. Source: Alan Bunner, Office of Space Science, NASA Headquarters, Washington, D.C. Reprinted with permission.

EXPLORING THE UNKNOWN 731 Document III-36 Document title: Letter to G. M. Mason, Associate Professor of Physics, University of Maryland, from Dr. Martin Weisskopf, Chief, X-ray Astronomy, NASA, May 1, 1987. Source: Alan Bunner, Office of Space Science, NASA Headquarters, Washington, D.C. In 1982, a National Research Council committee headed by astronomer George Field recommended that the Advanced X-ray Astrophysics Facility (AXAF) should be the nation's top priority in astrono- my because the mission was essential to answering many pressing astronomical questions. By the mid- 1980s, NASA's Space and Earth Science Advisory Committee (SESAC) had likewise expressed its support for major, observatory-class missions such as AXAF. Not all astronomers agreed with NASA's trend of pursuing larger, more ambitious missions. Warning that investing resources only in major, space-based observatories was highly risky, such scientists advocated that NASA apply the lesson learned from the 1986 Challenger disaster to depend on a “mixed fleet” of launch vehicles for its space science program and employ a mix of mission sizes. These letters, exchanged among a university pro- fessor, the SESAC chairman, and a NASA astronomer, illustrate the differences of opinion among astronomers regarding the merit and risks of major space-based observatories. [no pagination] Document III-35 THE UNIVERSITY OF MARYLAND COLLEGE PARK CAMPUS Department of Physics and Astronomy College Park, Maryland 20742 (301) 454-3401 Space Physics Tel: (301) 454-3135 Dr. L.J. Lanzerotti, Chairman Space & Earth Science Advisory Committee Bell Telephone Labs 600 Mountain Ave. Murray Hill, NJ 07974 RE: The ultra-high risk NASA space science programs Dear Lou, 26 March 1987 In the post-Challenger examination of NASA science programs, many promising pos- sibilities are being explored including the role of ELVs, moderate missions and possibly even an Explorer augmentation. These healthy discussions of future directions and strate-

732 NASA AND PLANETARY EXPLORATION gies leave out consideration of the fact that the OSSA community has inherited what can now be seen to be a program with ultrahigh risks in which the fates of major subdisciplines are tied to single pieces of hardware. There are several examples, but perhaps the best are the "Great Observatories": HST, GRO, AXAF and SIRTF. Since HST and GRO are basically finished, consider the case of AXAF. The United States X-ray astrophysics community, which has had no mission since the Einstein observatory in the late 70's, is tying its entire future to a single device that might be launched in the mid-90's. Last year's Challenger explosion, followed shortly thereafter by the immensely costly Titan launched reconais- sance [sic] satellite explosion, should remind us that failures will occur. Prudent science policy should ensure that when failures occur the results are not fatal, but indeed we now have several of our science subdisciplines thus exposed to single point failures. It seems to me that we got into this situation in the late 70's for two reasons. First, the credulous (including me) rated the chance of a Shuttle launch catastrophe to be negligi- bly low, and we believed also that the shuttle would provide frequent access to space. Given this premise, there is nothing silly about putting all your eggs in one basket, par- ticularly since any difficulties encountered in orbit could be fixed up on the next visit. I think it must now be admitted that this premise is bankrupt. Secondly, in the Field report a mission such as AXAF was promoted in the context of a vital, diversified Space Science program. The Field report not only recommended AXAF, it also recommended (pp 141- 143) three other new X-ray Explorers for the 80's. So, the program conceived by the Field committee was reasonable and balanced, given the premises accepted at the time. But we now have the reality which is: risky launch vehicles, no Explorers, and a 10-year stretchout of AXAF. What is now left of the original program is a tremendous high risk venture in which a major subdiscipline has unwittingly put its neck on the block. What can be done? I've occasionally asked NASA managers this, and get a response "but that's what the scientists want." Such responses are not adequate. The rationale for AXAF and other big missions was developed when NASA was advertising a super-reliable and inexpensive shuttle: take that away, along with the Explorers and moderate missions, and you have a whole new ball game. The X-ray astrophysics community is, unhappily, trapped in this situation. They have their AO and selction [sic], they've been blessed by all the appropriate committees, and they don't dare rock the boat for fear of being sent back to the starting gate. Step-by-step they've been led into a tremendously exposed and risky situation from which there is no obvious escape. I think that what must be done here is somewhat analogous to the mixed-fleet study: it must be recognized at the outset that the post-Challenger era is a new ball-game that requires rethinking of the old programs. Just as the mixed-fleet study recommends chang- ing implementation plans for launching certain missions, a reexamination of the super- risky OSSA programs may lead to revised implementations. Without this, we will have a situation wherein a large part of the 1990's will be spent with OSSA carrying out expen- sive and risky programs planned under seriously flawed premises. To allow this would be a serious mistake. OSSA cannot carryout such a sweeping reexamination of its programs by itself. However, I believe it should start out with the adoption of a management policy that avoids programs which expose the existence of entire subdisciplines to single point fail- ures. Advisory committees such as SESAC need to play a key role in any such reassessment,

 and this role in fairness should recognize the priority established for some programs even if they are significantly restructured. Since it is obvious that there will not be funds to build multiple copies of huge observatories, a less risky strategy would be to scale down any new ones to a size where it would be possible to carry on in parallel other Explorer-type missions in the same subdiscipline. Such a mix would help restore a healthy balance to the OSSA spectrum of program sizes, and is, I believe, better in keeping with the spirit of the Field report than the present single high risk missions. In my own area of low energy solar and cosmic ray research, we are uncoupled from these big, risky observatories. I have discussed the problem in terms of AXAF, but other big programs are in the same situation. I urge you and your committee to look into this very difficult problem, and seek to find ways to reduce the undue risks to which large segments of our space science community are now exposed. Sincerely, [signature] Glenn M. Mason Associate Professor of Physics cc: Dr. B.I. Edelson Dr. L. A. Fisk Mr: S.W. Keller Dr. J.D. Rosendhal Dr. C. Pellerin Dr. L. Peterson Mr. T. Perry Document III-36 [no pagination] ES65 Prof. G. M. Mason Associate Prof. of Physics Department of Physics and Astronomy University of Maryland College Park, Maryland 20742 Re: The "ultra-high risk” NASA space science programs Dear Prof. Mason: May 1, 1987 I have read with interest your letter to Dr. Lanzerotti and you certainly raise some interesting and thought provoking questions. I most certainly agree with your statements that balanced programs are a necessary ingredient for success in the Space Sciences. On the other hand, I totally disagree with your assessment of the situation concerning the discipline of X-ray astronomy in general and your discussion of the AXAF in particular. To me your letter makes the following assumptions which I comment on as follows: 1. There is no balanced program in X-ray Astronomy. Admittedly if one looks back at the last decade, X-ray astronomy would certainly appear to have come on hard times. Indeed this is true for all of high energy astro- physics which had its last “new start” in 1979 with the commencement of the GRO pro- gram. The fantastic results of the HEAO-2/Einstein which placed X-ray astronomy on equal footing with the more traditional astronomical disciplines makes this all the more surprising. On the other hand, if we look at current activities we see that a) the homework for AXAF is done and this major program is about to commence; b) there is a U. S. instrument and guest investigator program in collaboration with West Germany on the ROSAT satellite; c) the X-ray Timing Explorer is being studied and is definitely in the Explorer queue and d) there are a wide variety of sounding rock- et, balloon, and small (Scout Class) programs underway. Thus, although not neces- sarily ideal, it is certainly incorrect, today, to draw the conclusion that there is not a balanced NASA program in this discipline. The conclusion was true 10 years ago. 2.) The X-ray Astrophysics Community (with AXAF) is unhappily trapped. We are trapped, but not because we support the AXAF. As the SESAC itself has recommended, “Major facility-class missions have become essential for answering fundamental scientific questions in each of the Space and Earth Science disciplines and must be provided in turn on an appropriate schedule." The AXAF emerged as the number one priority from the Field Committee because it is essential for the science it can accomplish, and not simply to fill a menu of small, medium and large. The trap that we are in is the difficulty we have faced in getting the AXAF program started. 3.) AXAF is ultra high risk For many not intimately connected with the space program the Challanger [sic] accident came as a rude awakening that things can go wrong. But, a more careful examination of space launches from sounding rockets on up would show, in fact, that, if one considers all the types of failures that can and have taken place to prevent sci- entific accomplishment, the risk is more or less the same independent of the size of the venture. Thus, I feel, the more relevant issue is what is the pay off for the risk? In the case of X-ray astronomy, even a slew of smaller less ambitions missions of limited duration and scope have extremely limited return. They are incapable of addressing the fundamental questions and of serving the larger astronomical community. They do of course serve to keep the smaller X-ray community alive, but for what purpose? Admittedly if they fail, “few” dollars are lost (although the typical Explorer may cost well over 200 million in the 1990's) but how much is gained? If AXAF is successful, the life and vitality of the discipline, as whole, are guaranteed for more than a decade and astronomy and astrophysics will take a gigantic step forward. A second point, also worth emphasizing, is that, in a macabre but very real, way, the Challanger [sic]accident has lessoned [sic] not enhanced, the risk for AXAF because of the great visibility and emphasis placed on the program to put the shuttle in operational

EXPLORING THE UNKNOWN 735 status again and the implications for the future of the Agency, should another failure occur. 4.) Smaller is better There is always a vague feeling, amongst many scientists, that smaller is better, more productive, and of higher scientific yield. I think the real truth is that, for the working experimentalist, smaller is more fun. The really crucial factor, as Martin Harwitt has noted, is improvement in sensitivity and expansion of parameter space. This may be accomplished either in the large or in the small. In astronomy, size (aper- ture) and angulation of the telescope are the vital factors and X-ray astronomy is no exception. The AXAF telescope's properties are required to answer the questions we now pose and the sensitivity enhancements justify the claims of potential unforeseen exciting discoveries and breakthroughs. To me, your suggestion of descoping AXAF and spreading the resources to a number of smaller, “less risky” missions is equivalent to the idea of legislating that one should only build a number of 16" telescopes in as opposed to one large diameter telescope because of a perceived higher risk of failure of the latter. Sincerely yours, [signature] Dr. Martin C. Weisskopf Chief, X-ray Astronomy Document III-37 Document title: "Report of the HST Strategy Panel: A Strategy for Recovery," August- October, 1990. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. Document III-38 Document title: NASA, “Report of the Task Force on the Hubble Space Telescope Servicing Mission," May 21, 1993. Source: NASA Historical Reference Collection, History Office, NASA Headquarters, Washington, D.C. NASA and the international astronomical community were shocked when they learned in June 1990 that the Hubble Space Telescope had been launched with an incorrectly shaped primary mirror. The nature and cause of the problem with the mirror was quickly identified as being a “spherical aberra-

736 NASA AND PLANETARY EXPLORATION tion" not detected during the testing of the mirror before launch. (Volume I, Document IV-19). The issue was how to correct for the problem. This report represents the response of a special committee set up to address this question. The recommendations of the HST Strategy Panel were accepted by NASA, and used as the basis for planning the first Hubble Space Telescope Mission, which took place in December 1993. Given the difficulty and high stakes involved in this mission, NASA wanted to make sure that all elements of the mission were well understood, and that the hardware and mission crew were well prepared. An external review committee headed by Apollo-era NASA manager Joseph Shea was constituted as part of the process of providing such mission assurance. [title sheet] Document III-37 REPORT OF THE HST STRATEGY PANEL: A STRATEGY FOR RECOVERY THE RESULTS OF A SPECIAL STUDY AUGUST-OCTOBER 1990 EDITED BY R. A. BROWN AND H. C. FORD [1] PREFACE Astronomers and engineers realized that there was a problem with the images of Hubble Space Telescope (HST) shortly after it was launched in April 1990. The quality of the images failed to improve despite attempts to adjust the align- ment of the optics. NASA concluded in June 1990 that the HST primary mirror had been manufactured with the wrong shape. Compared with the desired profile, the mirror surface is too low by an amount that from the center to the edge grows from zero to 0.002 mm or four wavelengths of optical light. NASA convened an investigatory board in July 1990 under Dr. Lew Allen, which reported in November 1990 how the error probably occurred. In late 1980 or early 1981, a technician had improperly assembled a measuring device used to figure the primary mirror. Though tests at the time indicated a problem, the warning was not heeded, and the HST was assembled and launched with the flawed mirror. The deformity of the HST mirror causes spherical aber- ration in the images. This means light rays come to a focus at Secondary Mirror: 2.4 m Primary 43 mm Mirror -38 mm- -Paraxial Focus Marginal. Focus, Figure 1. Spherical aberration means that light rays from different radii on the primary mirror come to focus at different distances. The marginal focus is 38 mm below the focus of the innermost rays, which graze the secondary mirror. The paraxial focus is obscured. Currently, the adopted focus (not shown) is 12 mm below the paraxial focus.

EXPLORING THE UNKNOWN 737 different distances depending on the radius at which the rays strike the mirror, as shown in Figure 1. Light from the edge of the primary mirror comes to a focus about 38 mm beyond where the innermost rays converge. No positions, orientations, or other adjustments of the primary and secondary mirror can produce the diffraction-limited images required by much of the HST science pro- gram. The center of a star image in visible light has a core of radius 0.1 arcsec containing about 15% of the light; 70% was expected. The rest is spread about in a complex halo of radius 3 arcsec. Since aperture diffraction sets the size of the image core, the size is small- er at shorter wavelengths. The size of the halo, on the other hand, is set by geometrical optics and is constant. (The pattern of the halo varies with wavelength because it is an interference pattern.) Spherical aberration degrades the science capacity of HST. Good science is being accomplished with HST as it is, but many crucial investigations-including many of the orig- inal justifications for HST-are on hold until the problem is solved. [2] When the optical problem was announced, NASA began to seek solutions and devel- op a recovery plan. In the first phase, NASA focused on how to modify the scientific instru- ments already under development. These instruments are the Space Telescope Imaging Spectrograph (STIS), the Near-Infrared Camera and Multi-Object Spectrometer (NIC- MOS), and the second Wide Field and Planetary Camera (WFPC II), which NASA began to build in 1985 as a "clone" of the WFPC now in HST. NASA found it is feasible to cor- rect these future instruments to compensate for spherical aberration. Based on this find- ing, NASA adopted an initial baseline plan to install the corrected WFPC II in place of WFPC on the first servicing mission in 1993, and later, on a second mission in 1996, to install STIS or NICMOS either to recover spectroscopic capabilities (in the case of STIS) or to add new infrared capabilities (with NICMOS). This initial recovery plan of NASA restored faint source detection, one of the most critical capabilities crippled by spherical aberration. However, the plan delayed improving spectroscopy until the second half of the HST mission, and did not address full-resolution imaging at all. For these reasons, the HST Strategy Panel was formed in mid-August 1990 with a charter to search briskly for additional or alternative solutions. In this second phase of NASA study, the HST Strategy Panel sought the best over- all strategy to recover all primary HST science capabilities at an early time. The Panel did not adopt the WFPC II fix as a groundrule, but started “with a clean sheet of paper;" and tried to identify and review all potential options to alleviate the negative effects of spherical aberration on the HST science program. However, the Panel's rec- ommendations and deliberations were firmly rooted in the assumption that the sched- ule for the two second generation instruments, STIS and NICMOS, would be adhered to by NASA. The HST Strategy Panel's findings and recommendations were presented to Dr. Riccardo Giacconi, Director of the Space Telescope Science Institute, on October 18,1990. The Panel proposed a new program component as part of an augmented recov- ery strategy. The new component is the Corrective Optics Space Telescope Axial Replacement (COSTAR), a device to deploy corrective optics in front of the Faint Object Camera (FOC), High Resolution Spectrograph (HRS), and Faint Object Spectrograph (FOS). The strategy is to install both COSTAR and WFPC II into HST on the first servic-

738 NASA AND PLANETARY EXPLORATION ing mission in 1993, and to fix the HST pointing problems. This strategy recovers essen- tially all the science capabilities expected at launch. Dr. Giacconi endorsed the oral recommendations of the Panel and took the find- ings to NASA management. The Panel made a presentation at NASA Headquarters on October 26, 1990. In the following weeks, NASA conducted an intensive study of the fea- sibility and costs of COSTAR. In December 1990, NASA Headquarters authorized the implementation of the COSTAR program to proceed. [3] SYNOPSIS The HST strategy panel held four meetings between mid-August and mid-October 1990. At these meetings, a wide variety of options for correcting spherical aberration were identified and debated. This report, as outlined below, presents the Panel's findings and recommendations. The OPTICAL PROBLEM is now understood well enough to design and install a highly effective optical correction. The OPTICAL SOLUTION is a pair of mirrors for each Science Instrument (SI) field of view. The first corrective mirror forms an image of the HST primary mirror on the sec- ond corrective mirror; the second corrective mirror has spherical aberration in precisely the same amount as the primary mirror-but with the opposite mathematical sign, thus can- celling [sic] the effect. The COSTAR is the proposed device to carry and deploy the corrective optics for three scientific instruments, the FOC, HRS, and FOS. COSTAR would replace the High Speed Photometer (HSP). The POINTING of HST must be improved to gain full value from the restored HST opti- cal performance. The solar array "snap" that causes HST to lose pointing lock at day/night transitions must be fixed. The Panel further recommends that the operational parameters of the guidance system be adjusted to reduce jitter in the coarse tracking mode. The WFPC II is being corrected with the same optical solution used in COSTAR. The Panel found that the alignment of the corrective optics is critical, which COSTAR can assure by special mechanisms. No comparable mechanisms exist in the original design for WFPC, and because WFPC II is a close copy of the original, the Panel recommends that the issue of WFPC II alignment be addressed with critical attention. The 1993 SERVICING Mission can install the WFPC II and COSTAR. This currently planned mission can solve the spherical aberration problem for the SIs, fix the solar array disturbances, and replace other subsystems, as necessary. The RECOMMENDED STRATEGY is to develop COSTAR on an urgent basis, con- tinue WFPC II development with special attention to the alignment concerns, and improve the coarse track pointing performance by operational measures. Then, the 1993 HST servicing mission restores the scientific functionality expected at launch. The FRESH REASONS to commit new resources to fix HST are abundant in the sci- ence program awaiting sharp images and precise pointing. This science program is the culmination of decades, even centuries, of maturing questions about the universe. It is also a program proposed largely by young astronomers, who need a restored HST to make the discoveries that will propel astronomical exploration into the twenty-first century.

EXPLORING THE UNKNOWN 739 The APPENDICES document the approach, options, background findings, and analyses of the HST Strategy Panel. [pp. 5-119 not included] [cover page] Document III-38 REPORT OF THE TASK FORCE ON THE HUBBLE SPACE TELESCOPE SERVICING MISSION [1] 1. INTRODUCTION 21 May 1993 Washington, DC The Task Force was chartered by the Administrator of NASA, Daniel S. Goldin, to review all aspects of the first Hubble Space Telescope (HST) servicing mission scheduled for December 1993. Mr. Goldin, in a letter dated 26 January 1993 to Dr. Joseph F. Shea, Chairman of the Task Force, stressed the “importance, complexity, and visibility of this mission." The review was conducted over a period of five weeks (4 February 1993 through 9 March 1993) and centered on a series of informational briefings conducted at the Goddard Space Flight Center (GSFC), the Johnson Space Center (JSC), Lockheed Missile & Space Company Headquarters, and NASA Headquarters. The members of the Task Force are listed in Appendix 1 [appendices not included]. HST is one of the great orbital observatories planned by NASA. Launched 24 April 1990, HST can produce exceptional image detail for bright, high-contrast objects such as nearby star clusters, the cores of galaxies, and solar system planets. The HST has proved to be an extreme- ly valuable scientific resource and has already enabled several major discoveries. Despite its successes, HST has experienced a series of problems and anomalies. To correct for the problems and restore redundancy, a Space Shuttle crew will conduct the first servicing mission in December 1993. During the course of the review, it became clear to the Task Force that this mission is the most comprehensive and challenging on-orbit servicing mission NASA has ever attempted. It will require more extravehicular activity (EVA) than ever before planned for a single Space Shuttle mission. The mission has three basic goals: • Correct for spherical aberration of the primary mirror. Reduce the observatory's pointing fitter. Restore redundancy in key systems. Many of the servicing tasks are complex and all must be performed in a limited amount of time. During this time, astronauts will be asked to perform the following tasks:

 Install an optics package called the Corrective Optics Space Telescope Axial Replacement (COSTAR). Install a replacement for the current Wide Field/Planetary Camera (WF/PC I), called WF/PC II. • • Install two or more sets of gyroscopes and associated electronics. Replace the solar arrays. Install a computer co-processor. Install a repair kit for the Goddard High Resolution Spectrometer (GHRS). Replace the Magnetic Sensing System #1 (MSS-1) [2] In evaluating the effort required and the risks, it must be remembered that HST was designed for servicing and is therefore more compatible with crew servicing requirements than any other satellite produced to date. [3] 2. EVOLUTION OF HST SERVICING PLANS HST was designed and built for periodic on-orbit servicing. The current plan calls for servicing missions roughly every three years throughout the course of HST's 15 year life. Critical components are located in 50 unique types of orbital replacement units (ORUS). The ORUS were designed for easy access, removal, and replacement. In addition, 225 feet of crew translation hand holds and 31 portable foot restraint receptacles were provided on the surface of HST. These were placed to allow a servicing crew to move across the sur- face of the satellite, position themselves at any servicing location, and then reach the ORUS or related hardware. At the start of HST development in 1977, all HST components except wiring, struc- ture, thermal control surfaces and heaters, and the Optical Telescope Assembly optics were to be serviceable on-orbit. Early plans also included periodic return to Earth via the Shuttle for full refurbishment. In 1980, however, as part of a cost reduction program, the requirements for on-orbit serviceability was eliminated for a number of components, such as the multiple access transponder, the data management unit, the data interface units, the power distribution units, and the solar arrays. Four years later, the decision was made to eliminate ground return for periodic refurbishment as an option. This decision was based on unanswered technical concerns regarding the impact of ground return and relaunch, many of which still exist today. As an example, HST has strict contamination control requirements which are necessary for successful ultraviolet performance and which would be difficult to main- tain during ground return and servicing. In addition, as Shuttle-coupled loads increased, the predicted mechanical stresses on many HST primary structural elements increased to the point that fracture control restrictions limited the HST to a single launch. Another major consideration was the significant cost of ground return. Estimates indicated that manpower levels during refurbishment would approach those experienced during HST's initial development far exceeding the on-orbit servicing costs. Following the decision to eliminate HST ground return, an effort was initiated to sig- nificantly upgrade HST on-orbit serviceability. By that time, budget constraints had left only 20 unique ORUS with designs allowing complete EVA serviceability. EVA-compatible aids, such as captive fasteners, wing-tab connectors, tether loops, alignment decals, and connector maps, were added to the design of an additional 24 ORUS. This set of

EXPLORING THE UNKNOWN 741 redesigned ORUS is now referred to as Block II, while the original set of 20 ORUS is referred to as Block I. A third category, Block III, is composed of six ORU spares which were minimally enhanced to support EVA serviceability. These three blocks of ORUS have decreasing levels of EVA compatibility, but collectively enhance the basic serviceability of the HST design. Table 2.1 below, [4] provided by the HST Flight Systems and Servicing Project lists the candidates for repair or replacement during the first servicing mission and their block designation. TABLE 2.1 PAYLOAD COMPLEMENT AND PRIORITIES Item Priority Class Priority Block Sequence Solar Arrays (SA) 1 1 I Wide Field/Planetary Camera II (WF/PC II) 1 2 I Corrective Optics Space Telescope Axial 1 2 I Replacement (COSTAR) Rate Sensor Unit-2 (RSU-2) 1 3 I Coprocessor 1 4 I RSU-3 1 5 I Electronic Control Unit-3 (ECU-3) 1 6 I Goddard High Resolution Spectrograph 2 7 I (GHRS) Repair Kit Magnetic Sensing System-1 (MSS-1) 2 8 III ECU-1 2 9 I Fuse Plug 2 9 I RSU-1 2 9 I MSS-2 Blanket 3 10 N/A Although design compromises were made which reduced the EVA serviceability of certain ORUS, the Task Force believes that in-orbit serviceability is adequate and lower risk than ground servicing. Ground return should be considered only in the event of equip- ment failures which threaten HST and cannot be remedied by on-orbit servicing. ******** [7] 4. REQUIREMENTS AND PLANS FOR THE FIRST SERVICING MISSION The first HST servicing mission is designed to restore the full scientific capability to the spacecraft and to ensure the telescope systems continue to function and produce qual- ity observations. The current priority of the various repairs has been divided into two cat- egories - primary and secondary, as shown in the following table (Table 4.1) provided by the HST Project, Associate Director's Office. The primary repairs are those which are nec- essary for the mission to be regarded as successful. The secondary objectives will be met as time and resources allow. The actual mission plan does not directly follow this sequence because of Shuttle and HST limitations.

 Table 4.1 HST First Servicing Mission Payload Overview Failure/ Anomaly Spherical Cause Response Comments Category Aberration Primary mission ground to wrong prescription WF/PC-III and COSTAR with corrective optics Correction Primary necessary to meet Level I requirements Solar Array Jitter Thermal Primary deformations of experiencing array structure Gyroscope Failures Gyro 4 and 6: generic problem with Bendix pulse rebalance loop hybrid circuits Gyro 6 motor spindown: random Solar Array II with thermal shielding and improved mechanical design Retrofit of spare rate sensing units with Teledyne hybrids Changeout of RSU 2 and 3 Solar Array deformations outside of design envelope causing unacceptable attitude transient motion 3 of 6 gyros necessary Primary to conduct science mission 5 gyros following first |Primary servicing mission increase failure tolerance failure of spin Changeout of motor power ECU-3 Change out of RSU-3 Primary already planned phase-open circuit most likely originating in electronics Gyro 1 shutdown: Change out of Investigation not yet Secondary short circuit RSU-1, ECU-1 complete causing fuse to and fuse plug open, most likely fuse plug originating in ECU circuitry GHRS LOW Voltage Intermittent open of lug solder joint DF-224 Memory Unit Failures Memory Unit 3: open of plated through hole on 7 layer board Memory Unit 4: failure of read/ write enable Augment memory with coprocessor/ shared memory unit Coprocessor/ shared memory augmentation Science date Problem believed to be generic board Primary problem Stress cycling of spare N/A boards proved tolerance Use of built in Secondary cross-strapping via redundancy requires Power Supply relay box Failure Magneto- meter Intermittent open on signal path of Replace Magnet Sensing System #1 switch over of entire HST data management Attitude/thermally induced Secondary Anomalies Gyro Fuse Derating V2 Not generic problem Appears to be improper fusing Under review for gyro power circuits 3.0 Amp fuse must carry 2.0-2.3 Amps for 27 sec. N/A [8] The requirements and order of priority are constamtly [sic] changing, given the extend- ed mission preparation period and the changing status of the observatory. This instability impacts the mission preparation and mission operations training. It also places an additional load on astronaut and support team training. An additional concern is the escalating nature of the mission. Starting with a few objectives, the mission has grown to an unprecedented num- ber of EVAs. While the rate of failures is not unusual for a spacecraft of this complexity, the current servicing plans include replacing some very large and sensitive ORUS. The HST Project, the integration contractors, and the mission operations personnel have done a good job of pre-mission design and preparation for the periodic servicing of HST given the changing servicing philosophy throughout the development of the program. The devel- opment of EVA tasks, tools, and support hardware has progressed over the years of designing and building the HST. The prelaunch verification of the tools, including fit-checks to the flight unit and manned thermal vacuum testing and the planning for verification prior to the first servicing mission, has been methodical and adequate. Although a great deal of planning and care has clearly gone into contamination con- trol, the Task Force is concerned about the possibility for contamination of HST optics and other sensitive systems during the EVA. Possible sources of contamination include the EVA suits and tools. We recommend that orbital testing be conducted prior to the servic- ing mission to assess potential contamination using such techniques as witness plates. As the launch nears, there is the potential for new failures which could change the rel- ative priority of repairs and impact mission training and other preflight planning. New failures also have the potential to overload this single mission. This concern is heightened by the unknown causes of some of the existing failures. This mission already challenges the capability of the Shuttle and crew. In-depth planning for credible, but currently unknown, failures is required to prepare for this flight. Past EVA history suggests that complex EVAs often encounter unexpected events which can significantly alter plans and time lines. This experience, coupled with the com- plexity of this servicing mission strongly suggest the need to plan for a second servicing mission. A second mission may also be required to compensate for a greater than antici- pated failure rate following the initial mission. The schedule for the next planned mission may have to be accelerated or an additional mission may need to be inserted to maintain the telescope's health and enable the continuing science mission. [9] 5. MISSION MANAGEMENT AND TRAINING The HST servicing mission is the most complex Shuttle mission ever attempted. The accompanying mission planning and training also are quite complex. Mission preparation activities are managed by the Space Shuttle Program within the Office of Space Flight. Mission planning and training primarily are the responsibility of the Johnson Space Center with sup- port from the Marshall Space Flight Center. The actual mission planning and training are accomplished by a large team composed of members from these two Centers and from the HST Program Office at the Goddard Space Flight Center. The Task Force commends the peo- ple involved in this mission for the tremendous amount of work they have already done in preparation for this mission. We recognize that more advanced planning and effort has gone into preparing for this mission than for almost any previous Shuttle mission. The Task Force, however, found the interfaces between the organizations involved to be numerous and confusing. No single individual was charged with addressing all of the issues which might arise during mission preparation and who would be totally accountable for mission success. This problems appears to be under work, however. In response to criticism by various review teams, a mission director has been assigned by NASA Headquarters. Effective cooperation between the Centers involved in this mis- sion is absolutely essential to its success. A more complete distribution of these data could result in a better overall examination of the options. There should be no reluctance to hear proposals based on shared information; it is an accepted fact that, in the end, a deci- sion must be made and that such a decision cannot be shared. A chief concern of the Task Force is the amount of work that must be completed dur- ing a single Space Shuttle mission. The mission preparation for the first servicing mission follows the standard mission planning and training format for Shuttle missions and thus places much of the work in the last year prior to launch. The training and operations products are currently on schedule. However, the number of servicing tasks, the tele- scope's complexity, and the large size and numbers of ORUs to be repaired or replaced make the first servicing mission an EVA job that is unprecedented, and thus strongly indi- cate that pre-mission planning should have begun earlier than in past EVA missions. Given the mission's complexity, we also recommend that back-up crew members be assigned to train for the critical mission tasks. Current EVA time line development activities indicate that four or possibly five days of EVA may be necessary to complete the objectives of this first servicing mission. In gen- eral, we find the current EVA time lines to have insufficient slack. The EVA time [10] required has increased over 25 percent during February alone. In addition, some of the hardware appears to be behind schedule (e.g., COSTAR). These factors raise concerns about the viability of the overall schedule and further support the need for accelerated mission operations preparation. ***** [14] 7. CONCLUSIONS AND RECOMMENDATIONS Conclusions 1. The Hubble Space Telescope (HST) system is well designed to meet its continu- ing mission objectives. This design includes adequate redundancy within the spacecraft, a satisfactorily structured repair and refurbishment plan, and long- term science upgrades. We judge the first servicing mission to be feasible. 2. A major amount of in-depth effort has been put into this mission and significant progress has been made. The coordination and cooperation among the Office of Space Flight, the Office of Planetary Science and Astrophysics, the Goddard Space Flight Center, the Johnson Space Center, and the Marshall Space Flight Center is especially noteworthy. 3. The mission is very complex and contains the following risks: • • The EVA time line is very tight and has grown about 25% during February. The EVA planning, training and scheduling is late, considering the complex- ity of the time line. The management structure has been diffuse. Recent changes are encourag- ing, but require further senior management attention. 4. The schedule of all activities between now and launch has inadequate margin. The principal replacement units are late and major testing still remains. 5. The component failure rate is worrisome: • The impact of failure rate on risk has not yet been adequately assessed. Some failures are not yet fully understood. No redundancy remains in some key areas (e.g., gyro systems). • The recent fine guidance sensor anomaly is a matter of concern. • Additional failures before the servicing mission could impact the planning schedule. 6. The current flight plan is designed solely for Orbiter 105. This limits flexibility as other Orbiters are less capable. 7. The current plan does not include verifying the operability of all redundant HST subsystems. 8. A major effort has been applied to controlling contamination. Orbital testing is needed to assess potential contamination from EVA suits and tools. [15] Recommendations 1. Focused management is essential to this mission. The recent management changes are positive and must be sustained. Close senior management attention, including formal reviews, must be continued to ensure that the new organization remains effective.

746 NASA AND PLANETARY EXPLORATION 2. Development of the EVA time line and choreography, including contingencies, is necessary in order to properly plan the entire mission and should be accelerated. As soon as the time line is available, it should be reviewed by senior management. 3. Training for the mission must include joint integrated end-to-end simulations of the EVA portions. 4. HST recovery and return to Earth should not be considered unless repair is not achievable on-orbit. The overall risk and cost of the return and refurbish option is not otherwise justifiable. 5. Assure that the upgrades to the Neutral Buoyancy Simulator (e.g., Nitrox, video and RMS) are completed in time to support the joint simulations. 6. Designate and train a backup EVA crew member now. 7. Ensure that the current plan to exercise on-orbit HST repair procedures on an earlier Shuttle flight is implemented. This should include the use of witness plates to assess potential contamination issues. 8. Reassess priorities of the repair sequence. Give higher priority to replacing all gyroscope units. 9. Plan now for an early contingency mission to cover potentially incomplete tasks from the first servicing mission or additional failures on the spacecraft. 10. Conduct a quantitative assessment to determine the risk of verifying the status of all subsystems (both A-- and B-sides) before the first servicing mission. 11. Conduct an integrated assessment of contamination control procedures and plans for the HST servicing missions. ******** [21] APPENDIX B TASK FORCE ON THE HUBBLE SPACE TELESCOPE SERVICING MISSION Membership List Dr. Joseph F. Shea, Committee Chairman Adjunct Professor of Aeronautics and Astronautics Massachusetts Institute of Technology Dr. Eugene E. Covert Professor of Aeronautics and Astronautics Massachusetts Institute of Technology Dr. Maxime A. Faget Chairman of the Board Space Industries, Inc. Dr. Richard L. Garwin IBM Fellow IBM T. J. Watson Research Center

EXPLORING THE UNKNOWN 747 Dr. George J. Gleghorn Maj. Gen. Ralph H. Jacobson (Ret.) President and CEO The Charles Stark Draper Laboratories Dr. Herbert Kottler Head, Aerospace Division Massachusetts Institute of Technology Lincoln Laboratories Mr. Edmund Nowinski Prof. Bradford Parkinson Gravity Probe B Hansen Experimental Physics Laboratories Stanford University Mr. Charles Roth Mr. Harris Schurmeier Lt. Gen. Thomas P. Stafford, USAF (Ret.) Stafford, Burke and Hecker, Inc. Document III-39 Document title: "AXAF Restructuring," Briefing for the NASA Administrator, August 15, 1992. Source: Alan Bunner, Office of Space Science, NASA Headquarters, Washington, D.C. More than a decade after the mission was proposed, the Advanced X-ray Astrophysics Facility (AXAF) received a new start in NASA's FY 1988 budget; limited space science funds, consumed in large part by the Hubble Space Telescope's development, accounted for most of this delay. Even after the new start, NASA had a tough battle to fight to keep AXAF alive. In addition to having to prove to Congress within three years that AXAF's mirrors could perform adequately (which NASA did), the agency had to find a way to reduce the mission's weight and complexity in order to reduce its cost. This was part of NASA's strategy of moving away from very large and costly missions. In 1992, NASA decided to restructure the mission to meet the new cost constraints. The most significant changes were to split the AXAF mission into two elements, with AXAF-I dedicated to imaging and AXAF-S devoted to spec- troscopy, and to reduce the numbers of mirrors and instruments that would fly. The restructuring was

748 NASA AND PLANETARY EXPLORATION projected to save $290.7 million of the project's original cost of $2,021.7 million. AXAF-I became the AXAF spacecraft that was successfully launched in 1999; the satellite was renamed Chandra after launch. The AXAF-S instrument was eventually flown on Japan's Astro-E mission, also launched in 1999; that mission failed. [no pagination] OBJECTIVES AXAF RESTRUCTURING AUGUST 15, 1992 AXAF PROGRAM RESTRUCTURING • • • . . PRESERVE THE SCIENCE MISSION REDUCE BUDGET GROWTH FROM FY93 TO FY 94 REDUCE PEAK YEAR FUNDING REQUIREMENTS REDUCE MISSION COMPLEXITY HOLD OR ADVANCE LAUNCH DATE PRODUCE ROBUST AND RESILIENT PROGRAM GAIN MAXIMUM BENEFIT FROM PREVIOUS EXPENDITURES PROGRAMMATIC GUIDELINES . ASSUME FY 93 BUDGET APPROVED • ASSUME BUDGET CAPPED AT $250M PLUS INFLATION BEYOND FY93 • REDUCE OPERATIONS AND SERVICING BUDGET BY 30% • REDUCE MISSION COMPLEXITY • • . SEEK LOWEST COST LAUNCH OPTIONS HOLD OR ADVANCE THE BASELINE LAUNCH DATE OF 4/99 MAXIMALLY EMPOWER PRIME CONTRACTOR FOR AXAF-I PERFORM AXAF-S IN-HOUSE AT MSFC PROCESS AXAF TEAM BEGAN WORK IN JANUARY TO FIND OPTIONS WHICH WOULD MEET OBJECTIVES • MANY OPTIONS (19) IDENTIFIED AND EVALUATED. . • AXAF TEAM RECOMMENDATIONS TO AA/OSSA ON APRIL 30,1992 RESTRUCTURED AXAF INTO TWO COMPONENTS PROCESS CONTINUED TO DEVELOP MANAGEMENT STRATEGIES AND IMPLE- MENTATION ASPECTS DEVELOPMENT OF AXAF-S AT MSFC • AXAF-I and AXAF-S separate programs with distinct budgets but: maximize common buys and shared expertise AXAF-S

. • EXPLORING THE UNKNOWN 749 - Risk is substantially reduced by: - Technical synergy between AXAF-I and AXAF-S at MSFC Management flexibility between AXAF-I and AXAF-S at MSFC - Centralized science and technical management of both missions - Demonstrated enthusiastic response to in-house development at MSFC RESULTS program architecture - two components - high spatial resolution imaging (AXAF-I) -- 4 mirrors, 2 focal plane instruments, 2 gratings, Titan IV/centaur or STS/upper stage to high altitude elliptical orbit high energy, high spectral resolution spectroscopy (AXAF-S) -- - foil or replicated mirrors, polar orbit, 1 focal plane instrument, Delta launch to polar orbit separate, lighter mission for imaging permits high elliptical orbit -- high orbit mission is simpler and has better observing efficiency than baseline -- fewer instruments on each mission element means less time-sharing. -- offsets throughput and lifetime considerations -- comparable to baseline mission for imaging science spectroscopy mission uses simpler, lighter and cheaper metal foil or replicated mir- rors (decision 9/92). programmatic guidelines are met with 9/98 launch of AXAF-I and AXAF-S as soon as possible thereafter management strategy guidance -- implement innovative management strategies to save substantial funding on imaging mission. -- AXAF-S to be done in house with primarily govt [sic] labor. [image not supplied]

 AXAF RESTRUCTURING PARAMETER Orbit OLD BASELINE 600 Km Circular On-Orbit Weight Launch System Operational Life Launch Date Mirror Configuration Focal Length Focal Plane SI's Gratings MSFC ROLE CONTRACT MONITORING IN-HOUSE EFFORT 32,800 Lbs. Shuttle/ASRM 15 Years W/Servicing April, 1999 6 Mirror Pair HRMA 10 Meters HRC, ACIS, XRS HETG and LETG AXAF OLD BASELINE Maximum penetration of contractor AXAF-I 10,000 X 100,000 Km (STS) 60,000 X 120,000 (T-IV) < 11,500 Lbs. Shuttle/Upper Stage or Titan IV/Centaur 5 Years September, 1998 4 Mirror Pair HRMA 10 Meters HRC, ACIS HETG and LETG IMPLEMENTATION AXAF-I Significant MSFC in- house redundancy of contractor effort Maximal contractor empowerment with emphasis on incentive/ award fees Selective MSFC task redundancy in high risk areas AXAF-S 600 Km/Polar Sun Sync. < 6000 Lbs. Delta II 3 Years December, 1999 Foil or Replicated Mirrors 3.5 to 5.0 Meters XRS None AXAF-S Expect only S/C subsystems and SI's to be contracted for Develop in-house at MSFC with flexibility to phase staff in and out of project ******* AXAF ISSUES (1) HAVE ADEQUATE RESERVES BEEN IDENTIFIED AND ALLOCATED? (2) WHAT IS THE APPROPRIATE CENTER ASSIGNMENT FOR AXAF-S? RESERVE POSTURE Comparison of AXAF-I and AXAF-S reserves with the old baseline POP 92-1 reserves: POP 92-1 AXAF-I AXAF-S 20.8% 20.5% 17.7% RESERVE LEVELS ARE ACCEPTABLE: • • AXAF-I - Simplified derivative of the old baseline - High earth orbit - simpler comm., thermal, power, ops, etc - fixed HRMA No servicing

EXPLORING THE UNKNOWN 751 - P1/H1 success - metrology debugged HDOS now ahead of schedule AXAF-S - - Maximum flexibility as an in-house development project. - Instrument design mature, but will descope if cost growth appears Mirror technology demonstrated (Foil on BBXRT, Replicated on XMM) Document III-40 Document title: Structure and Evolution of the Universe Subcommittee of the Space Science Advisory Committee, NASA, “Cosmic Journeys: To the Edge of Gravity, Space, and Time Structure and Evolution of the Universe Roadmap 2003-2023,” September 1999. - Source: Office of Space Science, NASA Headquarters, Washington, D.C. For more than 40 years, NASA has crafted a program of space-based astronomy missions that have explored the universe in every major wavelength range between radio waves and gamma rays. The direction of that program has largely been influenced by the various groups of non-NASA astronomers to whom the Agency has looked for input throughout its existence. The situation is no different today. This document, created by NASA's current astronomy advisory group made up of scientists from out- side the Agency, reflects the objectives of astronomers for exploring the universe at the end of one cen- tury and into the next. [cover sheet] Cosmic Journeys To the Edge of Gravity, Space, and Time Structure and Evolution of the Universe Roadmap: 2003-2023 prepared by The Structure and Evolution of the Universe Subcommittee of the Space Science Advisory Committee National Aeronautics and Space Administration September 1999 [no page number] Executive Summary The Roadmap for the Structure and Evolution of the Universe (SEU) Theme embraces three fundamental, scientific quests:

 • To explain structure in the Universe and forecast our cosmic destiny To explore the cycles of matter and energy in the evolving Universe To examine the ultimate limits of gravity and energy in the Universe We develop these quests into six focused research campaigns: • • • • • Identify dark matter and learn how it shapes galaxies and systems of galaxies Explore where and when the chemical elements were made Understand the cycles in which matter, energy, and magnetic field are exchanged between stars and the gas between stars Discover how gas flows in disks and how cosmic jets are formed Identify the sources of gamma-ray bursts and high-energy cosmic rays Measure how strong gravity operates near black holes and how it affects the early Universe These campaigns lead to a portfolio of future major missions of great scientific inter- est and popular appeal, strongly endorsed by the scientific community. Many have under- gone significant initial study. Some are in a state of readiness that make them ideal candidates for the present Office of Space Science Strategic Plan; others may well feature in the next plan. Each provides a golden scientific opportunity to advance our under- standing of the Universe. We have identified three top-priority near-term science objectives together with mis- sions to accomplish these goals. The three problems span a diverse range of subdisci- plines, of observational technique, of timescales, and of cost, and are thus complementary, forming a coherent core program for the SEU theme in the 2003-2007 timeframe. • • • Obtain precise measures of the chemical composition and physical condi- tions in objects ranging from the closest stars to the most distant quasars via X-ray spectroscopy of unprecedented sensitivity. Utilize, for the first time, gravitational radiation as a probe of supermassive black holes throughout the Universe, compact binary sources within our Galaxy, and a possible gravitational wave background, using a 5 million kilo- meter arm-length laser interferometer in space. Determine the nature of the highest-energy cosmic rays, one of the most important questions in this fundamental field, via a measurement of the char- acteristics of individual elements over a wide range of mass and energy, uti- lizing the International Space Station as a platform. We also describe a small number of exciting missions which are strong candidates for new start status in the midterm, 2008-2013, pending technology development. These mis- sions tackle fundamental problems through the entire electromagnetic spectrum, from the radio through gamma rays, and in many cases develop fascinating technologies with applicability not only elsewhere in NASA but outside of space science as well. Finally, we describe a set of “vision missions," which stretch our scientific imagination and set tech- nology challenges for our field. A vigorous program of education and public outreach will bring the wonderful array of past and current scientific achievements in this theme to the public.

Biographical Appendix B James M. Beggs (1926-) was nominated by President Reagan on June 1, 1981, to become administrator of the National Aeronautics and Space Administration. He was the sixth individual to head the nation's civilian space agency. Beggs took his oath of office as head of the agency and entered the new post on July 10, 1981. Prior to his appointment as NASA administrator, Beggs had been executive vice president and a director of General Dynamics in St. Louis, Missouri. Beggs served with NASA from 1968 to 1969 as associate administrator for advanced research and technology. From 1969 to 1973, he was under secretary of the U.S. Department of Transportation. He went to Summa Corporation in Los Angeles, California, as managing director for operations, and then joined General Dynamics in January 1974. Prior to joining NASA, he had been with Westinghouse Electric Corporation in Sharon, Pennsylvania, and Baltimore, Maryland, for thirteen years. His resignation from NASA was effective on February 25, 1986. Since leaving NASA, Mr. Beggs has worked as a consultant from his offices in Bethesda, Maryland. See “Beggs, James M.,” biographical file, NASA Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, D.C. Lloyd Berkner (1905–1967) was involved in most of the early spaceflight activities of the United States in some capacity. Trained as an electrical engineer, he was at first interested in atmospheric propagation of radio waves, but after World War II became a scientific entrepreneur of the first magnitude. He was heavily involved in the planning for and execution of the International Geophysical Year in 1957 and 1958, and served in a variety of positions in Washington, DC, where he could influence the course of science policy. See “Berkner, Lloyd V.,” bio- graphical file, NASA Historical Reference Collection. Hans Bethe (1906- ) was born in Strasbourg, Alsace-Lorraine. A mathematical prodigy, he received a Ph.D. in physics in 1928 from the University of Munich. After Hitler came to power in Germany, he left for England and then the United States, landing at Cornell University in 1935. A key figure in atomic physics, he was the head of the Los Alamos theoretical division from 1943 to 1945. After having helped develop the atomic bomb, he later became an outspoken advocate of nuclear arms reduction. He won a Nobel Prize in 1967 for his discovery of how stars nourish their nuclear fires. See “Bethe, Hans A.," biographical file, NASA Historical Reference Collection. Albert Boggess served as the Hubble Space Telescope project scientist for operations at NASA's Goddard Space Flight Center in the 1980s. He also served as the project scientist for the International Ultraviolet Explorer space- craft from its development phase through the first several years of operation, including its January 1978 launch. See "Boggess, Albert," biographical file, NASA Historical Reference Collection. Detlev Bronk (1897-1975) was president of the National Academy of Sciences, 1950-1962, and a member of the National Aeronautics and Space Council. A scientist, he was president of the Johns Hopkins University from 1949 to 1953 and Rockefeller University from 1953 to 1968. See “Bronk, Detlev,” biographical file, NASA Historical Reference Collection. Percival Brundage (1892-1981) was the director of the Federal Bureau of the Budget during the Eisenhower administration. He earned an A.B. cum laude from Harvard University in 1914 and joined the New York staff of Price Waterhouse & Company accounting firm immediately after graduation. In 1930, he was made a partner of the firm and was a senior partner when he left to enter government service. He served as president of the American Institute of Accountants and chairperson of the executive committee of the New York Chamber of Commerce. See Marjorie Dent Candee, Current Biography Yearbook: 1957 (New York, NY: The H.W. Wilson Company, 1958). C Claude Canizares (1945- ) is the Bruno Rossi Professor of Experimental Physics at the Massachusetts Institute of Technology (MIT) and director of the Center for Space Research. He came to MIT as a postdoctoral fellow in 1971 and joined the faculty in 1974, progressing to professor of physics in 1984. He is a principal investigator on NASA's Chandra X-ray Observatory, leading the development of the High Resolution Transmission Grating 753

Spectrometer for this major space observatory, and is associate director of the Chandra X-ray Observatory Center. He also has worked on several other space astronomy missions, including as co-investigator on the Einstein Observatory (HEAO-2). His main research interests are high resolution spectroscopy and plasma diag- nostics of supernova remnants and clusters of galaxies, cooling flows in galaxies and clusters, x-ray studies of dark matter, x-ray properties of quasars and active galactic nuclei, and gravitational lenses. Professor Canizares received B.A., A.M., and Ph.D. degrees in physics from Harvard University. He has authored or co-authored more than 135 scientific papers. He is a member of the NASA Advisory Council; chair of the Space Studies Board of the National Research Council; a member of the Board of Trustees of the Associated Universities, Inc.; for- merly chaired NASA's Space Science Advisory Committee; a member of the National Academy of Sciences; a fel- low of the American Physical Society; a corresponding member of the International Academy of Astronautics; and a fellow of the American Association for the Advancement of Science. See “Canizares, Claude R.," bio- graphical file, NASA Historical Reference Collection. George Carruthers (1939- ) won NASA's Exceptional Scientific Achievement Medal in 1972 for development of the first lunar-based space observatory, which was carried to the surface of the Moon by the Apollo 16 crew. A leading African American astrophysicist, Dr. Carruthers worked at the Naval Research Laboratory's Space Science Division at the time. He received his Ph.D. in aeronautical and astronautical engineering from the University of Illinois in 1964, and won national recognition in 1970 when an instrument he developed found molecular hydrogen in interstellar space. In 1977, he went through screening to become a mission specialist astronaut. See “Carruthers, George R.,” biographical file, NASA Historical Reference Collection. Jimmy Carter (1924- ) was the thirty-ninth president of the United States from 1977 to 1981. He served as a naval officer and businessman before entering politics in the Georgia State Legislature (1962-1966). He also served as the governor of Georgia from 1971 to 1975. See “Carter, Jimmy,” biographical file, NASA Historical Reference Collection. Subrahmanyan Chandrasekhar (1910-1995) was an astrophysicist who studied in India before moving to the United States in 1936. A specialist in the final stages of stellar evolution and white dwarf stars, he won a Nobel Prize in 1983. NASA named the Chandra X-Ray Observatory after him. See David Millar, Ian Millar, John Millar, and Margaret Millar, The Cambridge Dictionary of Scientists (Cambridge, England: Cambridge University Press, 1996) and http://chandra.harvard.edu/about/chandra.html on the Web. Bill Clinton (1946- ) was the forty-second president of the United States from 1993 to 2001. He earned a B.A. from Georgetown University and a law degree from Yale University, and also studied at Oxford University as a Rhodes Scholar. In 1976, he was elected attorney general of Arkansas, and in 1978 became the youngest gover- nor of the United States. Elected to the presidency in 1992, he served two consecutive terms before leaving office. See "Clinton, William Jefferson," biographical file, NASA Historical Reference Collection. Edgar B. Cortright (1923- ) earned an M.S. in aeronautical engineering from Rensselaer Polytechnic Institute in 1949, the year after he joined the staff of Lewis Laboratory. He conducted research at Lewis on the aerody- namics of high-speed air induction systems and jet exit nozzles. In 1958, he joined a small task group to lay the foundation for a national space agency. When NASA was created, he became chief of advanced technology at NASA Headquarters directing the initial formulation of the agency's meteorological satellite program, includ- ing projects Tiros and Nimbus. Becoming assistant director for lunar and planetary programs in 1960, Cortright directed the planning and implementation of such projects as Mariner, Ranger, and Surveyor. He later became deputy director, then deputy associate administrator for space science and applications. In 1967, he became deputy associate administrator for manned spaceflight, and later director of the Langley Research Center in 1968, a position he held until 1975 when he went to work for private industry, becoming president of Lockheed- California in 1979. See “Cortright, Edward M.,” biographical file, NASA Historical Reference Collection. D William Gould Dow (1895-1999) earned B.S., E.E., and M.S. degrees from the University of Minnesota. A fac- ulty member of the University of Michigan for over 30 years, he served as chair of the department of electrical engineering. During World War II he led research and development for the continuous wave ultra-high-fre- 754 quency high power transmitter at the Radio Research Laboratory at Harvard University. Dow published Fundamentals of Engineering Electronics (1937) and many other articles about electronics. He was a member of the American Society of Electrical Engineers, the Engineering Society of Detroit, the Cosmos Club (Washington, DC), and a fellow of the American Institute of Electrical Engineers and the Institute of Radio Engineers (now the Institute of Electrical and Electronic Engineers). See Who's Who in Engineering: 1964 (New York, NY: Lewis Historical Publishing Co., Inc., 1964). Hugh Latimer Dryden (1898-1965) was director of the National Advisory Committee for Aeronautics (NACA) from 1947 until the creation of the National Aeronautics and Space Administration (NASA) in 1958. He was named deputy administrator of the new aerospace agency, created in response to the Sputnik crisis. Before NASA, he was associate director of the National Bureau of Standards, where he had served since 1918 in scientific research. Influenced by Dr. Joseph S. Ames, who for many years was chairperson of NACA and was himself a pio- neer in aerodynamics, Dryden undertook a study of fluid dynamics at the Bureau of Standards while continuing his courses at the Johns Hopkins University Graduate School. The university accepted his laboratory work and he received his Ph.D. in mathematics and physics in 1919. He served as the deputy administrator of NASA until his death on December 2, 1965. For further information on Hugh Dryden see Michael Gorn, “Hugh L. Dryden's Career in Aviation and Space" in Monographs in Aerospace History, No. 5 (Washington, DC: National Aeronautics and Space Administration, 1996), or Richard K. Smith, The Hugh L. Dryden Papers, 1898-1965 (Baltimore, MD: The Johns Hopkins University Library, 1974). E Dwight D. Eisenhower (1890-1969) was the thirty-fourth president of the United States from 1953 to 1961. A Career U.S. Army officer, during World War II he was the supreme allied commander in Europe. As president, he was deeply interested in the use of space technology for national security purposes and directed that ballistic missiles and reconnaissance satellites be developed on a crash basis. For more information on Eisenhower's space efforts, see Rip Bulkeley, The Sputniks Crisis and Early United States Space Policy (Bloomington, IN: Indiana University Press, 1991); R. Cargill Hall, “The Eisenhower Administration and the Cold War: Framing American Astronautics to Serve National Security," Prologue: Quarterly of the National Archives 27 (Spring 1995): 59–72; Robert A. Divine, The Sputnik Challenge: Eisenhower's Response to the Soviet Satellite (New York, NY: Oxford University Press, 1993). F Michael Ference, Jr. (1911-1996) earned a Ph.D. in physics from the University of Chicago in 1936 and worked as a professor at the university from 1937 to 1946. Upon leaving the university, he worked for Signal-Corps Engineering Laboratories until 1953, serving as chief scientist from 1948 to 1951, and technical director from 1951 to 1953. He then became the chief scientist for Ford Motor Company's Scientific Laboratory, and was pro- moted to executive director in 1959. He was a member of the American Physics Society and chairperson of the Science-Engineering Activity Committee. His memberships also included the Geophysical Research Board, the National Academy of Sciences, and the Advisory Group on Weather Modification. He was the author of Analytical and Experimental Physics (1943). See Who's Who in Engineering: 1964 (New York, NY: Lewis Historical Publishing Co., Inc., 1964). James C. Fletcher (1919–1991) was the NASA administrator who gained the approval of the Nixon administra- tion on January 5, 1972, to develop the Space Shuttle as the follow-on human spaceflight effort of the agency. He also served as NASA administrator a second time from 1986 to 1989, following the loss of the Space Shuttle Challenger on January 28, 1986. Fletcher received an undergraduate degree in physics from Columbia University and a doctorate in physics from the California Institute of Technology. After holding research and teaching posi- tions at Harvard and Princeton Universities, he joined Hughes Aircraft in 1948, and later worked at the Guided Missile Division of the Ramo-Wooldridge Corporation. In 1958, Fletcher co-founded the Space Electronics Corporation in Glendale, California. He was later named systems vice president of the Aerojet General Corporation in Sacramento, California. In 1964, he became president of the University of Utah, a position he held until he was named NASA Administrator in 1971. Dr. Fletcher died at his home in suburban Washington on December 22, 1991. See “Fletcher, James C.,” biographical file, NASA Historical Reference Collection. 755

Gerald Ford (1913- ) (R-MI) was elected to the U.S. House of Representatives in 1948 and served there until he became vice president in 1973 following the resignation of Spiro Agnew. He was president of the United States from 1974 to 1977, following Richard M. Nixon's resignation. See “Ford, Gerald,” biographical file, NASA Historical Reference Collection. William Alfred Fowler (1911–1995) won the Nobel Prize for Physics in 1983 for his work with Subrahmanyan Chandrasekhar in the development of theories of element generation. He was awarded the Apollo Achievement Award in 1969, and the National Medal of Science, the nation's highest honor for scientific achievement, in 1974. He served on many science advisory boards, including NASA's Space Program Advisory Council from 1971 to 1973, and was a member of the Space Science Board of the National Academy of Sciences from 1970 to 1973 and from 1977 to 1980. Finally, he was the chairperson of the Office of Physical Scientists from 1981 to 1984. Fowler earned a bachelor's degree in engineering at Ohio State University and a Ph.D. from the California Institute of Technology in 1936. Upon earning his doctorate, he began research at the California Institute of Technology as an assistant professor of physics, and in 1982 he was named professor emeritus. See Who's Who in the World 10th Edition, 1991-1992 (Wilmette, IL: Marquis Who's Who, 1990). Herbert Friedman (1916-2000) earned his Ph.D. in physics from the Johns Hopkins University in 1940. He con- ducted his first experiments in rocket astronomy with a V-2 rocket in 1949. He performed hundreds of experi- ments including having traced the solar cycle variations of x-rays and ultraviolet radiations from the Sun and measured the ultraviolet fluxes of early-type stars. Dr. Friedman received the National Medal of Science, the nation's highest honor for scientific achievement, as well as numerous other awards and merits. His scientific and technical contributions included 50 patents and about 300 published papers. He served on many science advisory committees, including the President's Science Advisory Committee, the General Advisory Committee of the Atomic Energy Commission, and the Space Science Board of the National Academy of Sciences. See “Friedman, Herbert,” biographical file, NASA Historical Reference Collection. G Riccardo Giacconi (1932– ) became head of the Hubble Space Telescope Science Institute in 1981 and served through that spacecraft's launch. Previously he served as associate director of the High Energy Astrophysics Division of the Harvard-Smithsonian Center for Astrophysics. A pioneer in the field of x-ray astronomy, he led the team that sent up the first x-ray satellite, UHURU, in 1970. See “Giacconi, Riccardo," biographical file, NASA Historical Reference Collection. T. Keith Glennan (1905-1995) was the first administrator of NASA, formally established on October 1, 1958, under the National Aeronautics and Space Act of 1958. Within a short time after NASA's formal organization, Glennan incorporated several organizations involved in space exploration projects from other federal agencies into NASA to ensure that a viable scientific program of space exploration could be reasonably conducted over the long term. A resident of Reston, Virginia, for twenty years after his retirement, he moved to Mitchellville, Maryland, in the late 1980s. He died in Mitchellville on April 11, 1995. See “Glennan, T. Keith,” biographical file, NASA Historical Reference Collection. M. J. E. Golay (1902-1989) was an accomplished physicist and inventor. The author of over fifty scientific and technological publications, he was the owner of at least fifteen U.S. patents. Dr. Golay received his Ph.D. in physics from the University of Chicago in 1931 and became the developing engineer and later the chief scien- tist of the Computer Division of Signal Corporation Laboratories. His inventions included the Golay infrared detector, Golay delay line, Golay coils, and Golay chromatographic columns. See Who's Who in Engineering: 1964 (New York, NY: Lewis Historical Publishing Co., Inc., 1964). Leo Goldberg (1913-1987) was the director of the Kitt Peak National Observatory from 1971 to 1977. Previously, he served as a professor of astronomy and observatory director at the University of Michigan and Harvard University from 1948 to 1971. A former president of the International Astronomical Union and American Astronomical Society, he received three degrees, including his Ph.D., from Harvard. See “Goldberg, Leo,” bio- graphical file, NASA Historical Reference Collection. 756

Daniel S. Goldin (1940- ) initiated a revolution to transform America's aeronautics and space program dur- ing his tenure as NASA's longest continually serving administrator. Before coming to NASA, Goldin was vice pres- ident and general manager of the TRW Space and Technology Group in Redondo Beach, California. During a twenty-five-year career at TRW, Goldin led projects for America's defense and conceptualized and managed pro- duction of advanced communication spacecraft, space technologies, and scientific instruments. He began his career at NASA's Lewis Research Center in Cleveland, Ohio, in 1962, and worked on electric propulsion systems for human interplanetary travel. See “Goldin, Daniel,” biographical file, NASA Historical Reference Collection. Albert Gore (1948- ) (D-TN) was the forty-fifth vice president of the United States. Prior to being elected vice president in 1992, he served in the U.S. House of Representatives from 1977 to 1985 and in the U.S. Senate from 1985 to 1993. He graduated with a degree in government, with honors, from Harvard University in 1969, and attended Vanderbilt Law School after serving in the Vietnam War. In 2000, he received the Democratic Party nomination for president of the United States. See “Gore, Albert,” biographical file, NASA Historical Reference Collection. Charles F. Green received his bachelor's and master's degrees from the University of Kansas and, in 1915, joined the University of Illinois as a graduate assistant in mathematics. World War I interrupted his work and he enlist- ed in the Air Corps, serving overseas as a test pilot. Upon his return, he received his Ph.D. from the University of Illinois and remained on the staff until joining General Electric in Schenectady, New York, in 1929. Dr. Green was among the group of experts sent to Europe early in 1945 to investigate engineering achievements of the Axis powers. When he returned he brought with him information on the Germans' progress in guided missiles and jet aircraft, which he obtained by visiting their military, industrial, and research centers. See “Green, Charles F.," biographical file, NASA Historical Reference Collection. H Edmund Halley (1656-1742) was an English astronomer and physicist. He made a number of significant astro- nomical discoveries, including the well-known comet that bears his name. He also cataloged the stars of the Southern Hemisphere. See David Millar, Ian Millar, John Millar, and Margaret Millar, The Cambridge Dictionary of Scientists (Cambridge, England: Cambridge University Press, 1996), and The Encyclopedia Americana International Edition, Volume 13 (Danbury, CT: Grolier, Inc., 1996). Philip Handler (1910–1981) was chairperson of the Department of Biochemistry at the Duke University Medical Center. Dr. Handler served as president of the National Academy of Sciences from 1969 to 1981, where he was a leading spokesman for excellence in American scientific endeavors. In addition to his Academy presidency, Dr. Handler served as a member, and subsequently as vice chairperson and chairperson, of the National Science Board from 1962 to 1970. He was instrumental in the development of the National Science Foundation. See "Handler, Philip,” biographical file, NASA Historical Reference Collection. Harry H. Hess (1906-1969) was one of the ten members of the Lunar Sample Analysis Planning Team research- ing samples returned to Earth by the Apollo spacecraft. He was predominantly a geologist, serving as presidents of the Mineralogical Society of America and the Geological Society of America. Hess earned his doctorate at Princeton University and became the Blair Professor of Geology. During the Apollo era, he was chairperson of the Space Science Board of the National Academy of Sciences. See “Hess, Harry H.,” biographical file, NASA Historical Reference Collection. Richard A. Horner (1917-) has been associated with aerospace activities throughout his career. He served as a pilot in the U.S. Army Air Forces during World War II, and was director of flight test engineering at Wright Field, Ohio (1944–1945 and 1947-1949). He was promoted to colonel in 1948. Between 1950 and 1955, he was first technical director and then senior engineer for the Air Force Flight Test Center at Muroc, California. In May 1955, Horner became deputy for requirements in the office of the assistant secretary of the Air Force, and in 1957 he became assistant secretary of the Air Force for research and development. In June 1959, he left the Air Force to become NASA associate administrator. He resigned from NASA in July 1960 and became senior vice president of the Northrop Corporation. In 1970, he joined the E. F. Johnson Company as president and chief executive officer. See “Horner, Richard E.,” biographical file, NASA Historical Reference Collection. 

Edwin P. Hubble (1889-1953) was considered by many people to be the greatest astronomer of the twentieth century. Hubble made a number of key discoveries about the nature of galaxies, such as classifying them into spi- ral, elliptical, and irregular categories. Perhaps his most famous discovery became known as Hubble's Law and states that all galaxies except those closest to the Milky Way are receding from us and at speeds proportional to their distances from us. NASA's Hubble Space Telescope is named after him. See "Hubble, Edwin P.," biograph- ical file, NASA Historical Reference Collection. Josef Allen Hynek (1910–1986) contributed much to the world of astrophysics, but he is known best for his work in the study of UFO sightings. Hynek dedicated much of his life to the Air Force, working as a consultant in a special project assessing reports of UFO sightings, bringing a more scientific reputation to the field. In 1960, he became the chairperson of the department of astronomy at Northwestern University and was also the director of its Dearborn Observatory. He retired from that position in 1974 after founding The Center for UFO Studies in Evanston, Illinois, in 1972. Dr. Hynek is also credited for coining the phrase “Close encounters of the third kind," which was used in his 1972 book, The UFO Experience, and the movie of the same title. Dr. Hynek received his bachelor's degree and his doctorate from the University of Chicago. See “Hynek, Josef A.," biographical file, NASA Historical Reference Collection. J Karl G. Jansky (1905-1950) was a scientist at Bell Telephone Laboratories who discovered celestial radio waves in the early 1930s, founding the field of radio astronomy. See “Jansky, Karl G.," biographical file, NASA Historical Reference Collection. Lyndon Johnson (1908-1973) (D-TX) was elected to the U.S. House of Representatives in 1937 and served until 1949. He was a U.S. senator from 1949 to 1961, U.S. vice president from 1960 to 1963, and then the thirty-sixth president of the United States from 1963 to 1969. Best known for the social legislation he passed during his presi- dency and for his escalation of the war in Vietnam, he also was highly instrumental in revising and passing the leg- islation that created NASA. He showed his support for the U.S. space program as chairperson of the Committee on Aeronautical and Space Sciences and as chairperson of the Preparedness Subcommittee of the Senate Armed Services Committee. He later served as chairperson of the National Aeronautics and Space Council when he was vice president. On his role in support of the space program, see Robert A. Divine, “Lyndon B. Johnson and the Politics of Space," in The Johnson Years: Vietnam, the Environment, and Science, Robert A. Divine, ed. (Lawrence, Kansas: University of Kansas Press, 1987): 217–53; and Robert Dallek, “Johnson, Project Apollo, and the Politics of Space Program Planning," unpublished paper delivered at a symposium on “Presidential Leadership, Congress, and the U.S. Space Program," sponsored by NASA and American University, March 25, 1993. K Joseph Kaplan (1902–1991) was born in Tapolcza, Hungary, and came to the United States in 1910. He trained as a physicist at the Johns Hopkins University and worked on the faculty of the University of California-Berkeley from 1928 until his retirement in 1970. He directed the university's Institute of Geophysics, later the Institute of Geophysics and Planetary Physics, from the time of its creation in 1944. Kaplan was heavily involved in efforts in the 1950s to launch the first artificial Earth satellite, serving as the chairperson of the U.S. National Committee for the International Geophysical Year, 1953-1963. See “Kaplan, Joseph,” biographical file, NASA Historical Reference Collection; Joseph Kaplan, “The Aeronomy Story: A Memoir," in R. Cargill Hall, ed., Essays on the History of Rocketry and Astronautics: Proceedings of the Third Through the Sixth History Symposia of the International Academy of Astronautics (Washington, DC: NASA Conference Publication 2014, 1977), 2:423–27; Joseph Kaplan, “The IGY Program," Proceedings of the IRE, June 1956, 741–43. W. W. Kellogg (1917– ) was a meteorologist with the Rand Corporation between 1947 and 1959. He has held a senior position with the National Center for Atmospheric Research in Boulder, Colorado, since 1959. See Who's Who in America, 2000 Edition (New Providence, NJ: Marquis Who's Who, 1999). Ernst Henry Krause (1913- ) earned his bachelor's, master's, and doctorate degrees from the University of Wisconsin, then served as the associate director of research at the Naval Research Laboratory from 1938 to 758

1954. After leaving this post, he was the director of research laboratories, Missile Systems Division, at Lockheed Aircraft Corporation until 1955. He then became a member of the board of directors of Aeronutronic Systems, Inc. from 1956 to 1960. He was director of technical staff for the Aeronutronic Division of Ford Motor Company until 1962. After leaving Ford, he was the vice president of the Aerospace Corporation. Dr. Krause also served as a member of the Science Advisory Board in Redlands, California, and earned a Distinguished Civilian Service Award from the United States Navy. See Who's Who in Science from Antiquity to Present (Chicago, IL: Marquis Who's Who, Inc., 1968). L O. B. "Bill" Lloyd (1916–1990) graduated from Northwestern University's Medill School of Journalism in 1938, then became a staff member for U.S. Senator Lyndon B. Johnson (D-TX). He left this position in 1961 to join NASA as director of public services until retirement in 1979. He was awarded NASA's Exceptional Service Medal in 1969. See “Lloyd, O. B.,” biographical file, NASA Historical Reference Collection. George Harry Ludwig (1927- ) is credited as one of three discoverers of the Van Allen radiation belts. He earned his Ph.D. in electrical engineering in 1960 from the University of Iowa and began working at Goddard Space Flight Center in the Fields and Particles Instrumentation Section. After 12 years at Goddard (including service as associate director for data operations), Dr. Ludwig changed careers and began working for the National Oceanic and Atmospheric Administration (NOAA). His employment at NOAA in the National Environmental Satellite Service lasted for eleven years (1972-1983), during which he became the director of Environmental Research Laboratories. He served as assistant to the chief scientist at NASA Headquarters from 1983 to 1984, and was involved in the designing of the Space Station from 1983 to 1992. Additionally, Dr. Ludwig was the principle designer of radiation detection instrumentation for several scientific spacecraft, including Explorer 1. He oversaw development and operation for the United States National Environmental Satellite System from 1972 to 1980, and was awarded the Program Administration and Management Award from NOAA in 1977. He was also a Van Allen scholar (1958), a research fellow for the U.S. Steel Foundation (1958-1960), a recipi- ent of NASA's Exceptional Service medal (1969), and a recipient of NASA's Exceptional Science Achievement medal (1984). A life member of the Institute of Electrical and Electronics Engineers, he is also a member of the American Meteorological Society and the American Geophysical Union. See Who's Who in America, 2000 Edition (New Providence, NJ: Marquis Who's Who, 1999). M Neil H. McElroy (1904-1972) was U.S. secretary of defense from 1957 to 1959. He had previously been presi- dent of Procter & Gamble and returned there in December 1959 to become chairman of the board. He served in that position until October 1972, a month before his death. See “McElroy, Niel H.,” biographical file, NASA Historical Reference Collection. Carl Edwin McIlwain (1931- ) was on President Johnson's Science Advisory Committee on the Fields and Particles and Anti-Submarine Warfare subcommittees from 1964 to 1967. After receiving his Ph.D. from the State University of Iowa in 1960, he became a member of NASA's Space Science Steering Committee from 1962 to 1966, and, in 1967, he was a recipient of a Guggenheim fellowship. Additionally, Dr. McIlwain is a member of the American Institute of Physics and the American Geophysics Union. He has published works on measure- ments of charged particles producing bright auroral displays and Van Allen radiation. See Who's Who in Science from Antiquity to Present (Chicago, IL: Marquis Who's Who, Inc., 1968). Barbara Ann Mikulski (1936- ) (D-MD) became the first Democratic woman elected to the U.S. Senate in 1987. She was immediately elected chairperson of the Senate Appropriations Subcommittee on Veteran Affairs, Housing and Urban Development, and Independent Agencies, with jurisdiction over NASA. Though her sub- committee covers a wide range of subjects, she is best known in the science community for her defense of NASA during intense budget cuts. Because many Goddard Space Flight Center employees are Maryland residents, Senator Mikulski has fought countless battles for increased funding and against downsizing. She earned the American Astronautical Society's John F. Kennedy Award in 1995. See “Mikulski, Barbara Ann,” biographical file, NASA Historical Reference Collection. 759

Thomas A. (Tim) Mutch (1931–1980) was the NASA associate administrator for space science from 1979 to 1980, when he died in a climbing accident in the Himalayas. Previously a professor of geological sciences at Brown University, he led the Viking spacecraft's imaging science team from 1969 to 1977. He earned a Ph.D. in geology from Princeton University in 1960. See “Mutch, Thomas A.," biographical file, NASA Historical Reference Collection. N John E. Naugle (1923- ) was trained as a physicist at the University of Minnesota and began his career study- ing cosmic rays by launching balloons to high altitudes. In 1959, he joined NASA's Goddard Space Flight Center in Greenbelt, Maryland, where he developed projects to study the magnetosphere. In 1960, he took charge of NASA's Fields and Particles Research program. He also served as NASA's associate administrator for the Office of Space Science and as the agency's chief scientist before his retirement in 1981. See John E. Naugle, First Among Equals: The Selection of NASA Space Science Experiments (Washington, DC: NASA SP-4215, 1991). Homer Newell (1915-1983) earned his Ph.D. in mathematics at the University of Wisconsin in 1940 and served as a theoretical physicist and mathematician at the Naval Research Laboratory from 1944 to 1958. During part of that period, he was science program coordinator for Project Vanguard and was acting superintendent of the atmos- phere and astrophysics division. In 1958, he transferred to NASA to assume responsibility for planning and devel- opment of the new agency's space science program. He soon became deputy director of spaceflight programs. In 1961, he assumed directorship of the Office of Space Sciences; in 1963, he became associate administrator for Space Science and Applications. Over the course of his career, he became an internationally known authority in the field of atmospheric and space sciences as well as the author of numerous scientific articles and seven books, including Beyond the Atmosphere: Early Years of Space Science (Washington, DC: NASA SP-4211, 1980). He retired from NASA at the end of 1973. See “Newell, Homer,” biographical file, NASA Historical Reference Collection. Oran Nicks (1925-1998) was the deputy director of NASA's Langley Research Center from 1970 to 1980. Prior to this position, he was the deputy associate administrator of the Office of Space Science and Applications from 1968 to 1970 and the associate administrator of the Office of Advanced Research and Technology in 1970. He was also the director of Lunar and Planetary Programs from 1961 to 1968. Upon retiring from NASA, Mr. Nicks was the director of the Space Research Center at Texas A&M University from 1985 until his death in 1998. See "Nicks, Oran," biographical file, NASA Historical Reference Collection. 0 Hugh Odishaw (1916-1984) was assistant to the director of the National Bureau of Standards (1946-1954), served as executive director of the U.S. National Committee for the International Geophysical Year (1954–1965), and then became the executive secretary of the Division of Physical Sciences in the National Academy of Sciences (1966-1972). See “Odishaw, Hugh,” biographical file, NASA Historical Reference Collection. John O'Keefe (1917- ) is an astronomer who worked at the Goddard Space Flight Center from 1958 until 1995. Previously he worked for the Army Corps of Engineers doing geodesy for sixteen years. In 1992 he received NASA's Award of Merit. O'Keefe is an expert on tektites-small glassy meteorites. He received his Ph.D. in astronomy from the University of Chicago. See “O'Keefe, John A.,” biographical file, NASA Historical Reference Collection. William J. O'Sullivan (1915–1971) invented the world's first lightweight inflatable satellite, which was used for the first transcontinental telephone call via space. He was awarded a $5,000 NASA grant for his “significant con- tribution to space science and technology," and awarded the NASA Medal for Exceptional Scientific Achievement in 1961. In addition to being a NASA scientist, he also worked for the National Advisory Committee for Aeronautics. See “O'Sullivan, William J.," biographical file, NASA Historical Reference Collection. P Rocco Petrone (1926- ) was an instrumental member of the Apollo team. After earning his bachelor's degree at West Point and a master's degree in mechanical engineering from the Massachusetts Institute of Technology, Petrone worked at the Missile Firing Laboratory of the U.S. Army's Guided Missile Development Division at the 760

Redstone Arsenal in Huntsville, Alabama. Here he developed some of the launch vehicle technology used later in the Apollo launches. In 1959, he joined the NASA team and became Saturn project operator in 1960. Four years later he transferred to the Kennedy Space Center, where he was the director of Plans, Programs and Resources. In 1966, he was promoted to Apollo program manager, and after the success of the lunar landing, he became director of the Apollo Program in 1969. In 1973, he succeeded Dr. Eberhard Rees as director of the Marshall Space Flight Center, and became the third highest-ranking NASA official. He left NASA in 1975 to become president and chief executive officer of the National Center for Resource Recovery. See “Petrone, Rocco," biographical file, NASA Historical Reference Collection. William Pickering (1910- ) obtained his bachelor's and master's degrees in electrical engineering, then a doc- torate in physics from Caltech, before becoming a professor of electrical engineering in 1946. In 1944, he orga- nized the electronics efforts at the Jet Propulsion Laboratory (JPL) to support guided missile research and development, and became project manager for Corporal, the first operational missile JPL developed. From 1954 to 1976, he was director of JPL, which developed the first U.S. satellite (Explorer 1), the first successful U.S. cis- lunar space probe (Pioneer 4), the Mariner flights to Venus and Mars in the early to mid-1960s, the Ranger pho- tographic missions to the Moon in 1964-1965, and the Surveyor lunar landings of 1966-1967. See “Pickering, William H.," biographical files, NASA Historical Reference Collection. Richard Porter, an electrical engineer, worked on missile programs with the General Electric Company before working on Earth sciences programs at the National Academy of Sciences. In 1964, he was the Academy's dele- gate to the Committee on Space Research (COSPAR). He also chaired the Technical Panel for the Earth Satellite Program. See "Assorted Government Officials" biographical file, NASA Historical Reference Collection. Frank Press (1924- ) served as President Carter's science advisor and director of the Office of Science and Technology Policy from 1977 to 1981. Upon leaving this post, he was elected nineteenth president of the National Academy of Sciences. Press earned his Ph.D. in geophysics from Columbia University, and has earned twenty-eight additional honorary doctorates. See “Press, Frank,” biographical file, NASA Historical Reference Collection. William Proxmire (1915- ) (D-WI) was a U.S. Senator from Wisconsin who served from 1957 to 1989. He was well known for his “Golden Fleece Awards,” which he presented to various federal government agencies for pro- jects that he felt wasted taxpayers' money. See Biographical Directory of the American Congress, 1774-1996 (Alexandria, VA: CQ Staff Directories, Inc., 1996), and “Proxmire, William,” biographical file, NASA Historical Reference Collection. Ptolemy (87-150 A.D.) was a Greek mathematician who lived in the second century. His conception of the uni- verse as Earth-centered remained until Copernicus' theory was published in the sixteenth century. See “Ptolemy" biographical file, NASA Historical Reference Collection. Q Donald Quarles (1894–1959) was a deputy secretary of defense between 1957 and 1959. After World War II, he served as vice president for the Western Electric Company and later at Sandia National Laboratories, but in 1953 he accepted the position of assistant secretary of defense for research and development. He was also sec- retary of the Air Force between 1955 and 1957. See "Quarles, Donald," biographical file, NASA Historical Reference Collection. R Norman F. Ramsey (1915- ) is a physicist who shared the Nobel Prize in 1989 for his work on a cesium atom- ic clock and the hydrogen maser. He received his Ph.D. from Columbia University in 1940, after also studying abroad at Cambridge University. During World War II, he worked on radar systems and on the atomic bomb pro- ject at Los Alamos. After working as a professor at Columbia and helping found the Brookhaven National Laboratory, he became a professor at Harvard University in 1947, where he has worked ever since. See Emily J. McMurrary, editor, Notable Twentieth-Century Scientists, Volume 3 L-R, (New York, NY: Gale Research, Inc., 1995), and “Ramsey, Norman F.,” biographical file, NASA Historical Reference Collection. 

Ernest Clark Ray (1930- ) began work as an aerospace technologist at the Goddard Space Flight Center in 1965. He received his Ph.D. from the State University of Iowa in 1956, where he became an assistant professor of physics. He was a National Academy of Sciences fellow at Goddard Space Flight Center from 1962 to 1963, and is a member of the American Physics Society and the American Geophysics Union. He has researched and published works in theoretical studies of the motion of cosmic rays trapped in radiation in Van Allen radiation belts. See Who's Who in Science from Antiquity to Present (Chicago, IL: Marquis Who's Who, Inc., 1968). Ronald Reagan (1911- ) was elected as the fortieth U.S. President in 1980 and served two consecutive terms from 1981 to 1989. He was in office during the beginning of Space Station Freedom in 1984, and during the Challenger tragedy on January 28, 1986. A graduate of Eureka College, he was a radio announcer until 1937, when a screen test won him a contract with Hollywood. Over the following twenty years, he appeared in fifty-three films, was president of the Screen Actors Guild, and was a national spokesman for conservatism. In 1966 he was elected governor of California, paving the road to his nomination as the Republican Party candidate in the 1980 presidential election. See “Reagan, Ronald,” biographical file, NASA Historical Reference Collection. Eberhardt Rechtin (1926- ) was one of three engineers to design the digital image transmission system tech- nology that allowed us to receive pictures of Jupiter, Saturn, Uranus, and Neptune during the Voyager missions, and the radar technology that allowed mapping of the surface of Venus. He is the founder of the Deep Space Network (DSN), and worked at the Jet Propulsion Laboratory from 1949 to 1967. He was president and CEO of the Aerospace Corporation and assistant secretary of defense for telecommunications under President Nixon from 1972 to 1973. He earned both his B.S. and Ph.D. degrees from the California Institute of Technology. See “Rechtin, Eberhardt,” biographical file, NASA Historical Reference Collection. Bruno B. Rossi (1905-1993) was considered a pioneering figure in the study of high-energy astrophysics, x-ray astronomy, and interplanetary plasma (space physics). Born in Venice, he received a Ph.D. in physics from the University of Bologna in 1927. He left Italy in 1938 for Denmark and England, before coming to the United States and joining Cornell University's faculty in 1940. From 1943 to 1946, he worked at Los Alamos, where the atomic bomb was developed. Early in his career, he developed significant new techniques for observing cosmic rays. With his colleagues, he created a detector aboard the Explorer 10 satellite, which in 1961 discovered the mag- netopause, the edge of the Earth's magnetic field. After its launch in December 1995, NASA renamed its X-Ray Timing Explorer spacecraft in honor of Rossi; the spacecraft is now known as RXTE. See Bruno Rossi obituary, The New York Times, November 24, 1993, page D19, and “Rossi, Bruno B.,” biographical file, NASA Historical Reference Collection. S Robert C. Seamans, Jr. (1918- ) was born on October 30, 1918, in Salem, Massachusetts. He attended Lenox School in Lenox, Massachusetts; earned a B.S. degree in engineering at Harvard University in 1939; a M.S. degree in aeronautics at the Massachusetts Institute of Technology (MIT) in 1942; and a doctor of science degree in instrumentation from MIT in 1951. Dr. Seamans also received the following honorary degrees: doctor of science from Rollins College (1962) and from New York University (1967); and doctor of engineering from Norwich Academy (1971), from Notre Dame University (1974), and from Rensselaer Polytechnic Institute (RPI) in 1974. In 1960, Dr. Seamans joined NASA as associate administrator. In 1965, he became deputy administrator, retaining many of the general management-type responsibilities of the associate administrator and also serving as acting administrator. During his years at NASA, he worked closely with the U.S. department of defense in research and engineering programs, and served as co-chair of the Astronautics Coordinating Board. Through these associa- tions, NASA was kept aware of military developments and technical needs of the department of defense and Dr. Seamans was able to advise that agency of NASA activities that had application to national security. For further information on Robert C. Seamans, Jr., see his autobiography, Aiming at Targets (NASA SP-4106, 1996). Abe Silverstein (1908- ), who earned a B.S. in mechanical engineering (1929) and an M.E. (1934) from Rose Polytechnic Institute, was a longtime NACA manager. He had worked as an engineer at the Langley Aeronautical Laboratory between 1929 and 1943 and at the Lewis Laboratory (later, Research Center) in a succession of man- agement positions, the last (1961-1970) as director of the Center. When T. Keith Glennan arrived at NASA, Silverstein was on a rotational assignment to the development (later, space flight programs) from the position of associate director at Lewis, which he had held since 1952. During his first tour at Lewis, he had directed investigations leading to significant improvements in reciprocating and early turbojet engines. At NASA Headquarters, he helped create and direct the efforts lead- ing to the spaceflights of Project Mercury and to establish the technical basis for the Apollo program. As Lewis's director, he oversaw a major expansion of the center and the development of the Centaur launch vehicle. He retired from NASA in 1970 to take a position with Republic Steel Corporation. On the career of Silverstein see, Virginia P. Dawson, Engines and Innovation: Lewis Laboratory and American Propulsion Technology (Washington, DC: NASA SP-4306, 1991), and "Silverstein, Abe," biographical file, NASA Historical Reference Collection. John A. Simpson (1916- ) is the founder of the Laboratory for Astrophysics and Space Research at Enrico Fermi Institute for Nuclear Studies. Additionally, he is the Arthur H. Compton Distinguished Service professor emeritus at the University of Chicago, and the Martin Marietta chair in space history at the Smithsonian Institute's National Air and Space Museum. He earned his Ph.D. from New York University in 1943. See "Simpson, John A.," biographical file, NASA Historical Reference Collection. Tony Spear is a thirty-six-year veteran of the Jet Propulsion Laboratory (JPL) in Pasadena, California. As project manager for the Mars Pathfinder mission, he oversaw the mission from its conception to the successful landing in 1997. After the success of Viking Lander 1 in 1976, he stepped down from his position as project manager and joined the Advanced Deep Space System Development Program (called X2000). Upon joining NASA in 1962, he was an engineer in several positions. In 1974, he was the advanced projects planning manager for the NASA/JPL Deep Space Communications and Spacecraft Tracking Network. Spear was manager of the 1989 Magellan mission to map the surface of Venus, manager of the synthetic aperture imaging radar instruments that flew aboard several Space Shuttle missions in the early 1990s, and was an engineer on the 1978 Seasat oceano- graphic satellite mission. Spear earned a B.S. in electrical engineering from Carnegie Mellon University, an M.S. in electrical engineering from the University of Southern California, and an M.S. in mechanical engineering from the University of California-Los Angeles. He retired from JPL in 1998. For more information on Tony Spear, see the Media Relations Office at JPL. Athelstan Frederick Spilhaus (1911-1998) was born in Cape Town, South Africa, and earned a B.Sc. and D.Sc. from the University of Cape Town before coming to the United States in 1931. He then earned a S.M. from the Massachusetts Institute of Technology (MIT) in 1933, and a D.Sc. from Coe College in 1961. He was a research assistant at MIT from 1934 to 1935, and then became assistant director of technical services for the Union of South African Defense Forces until 1936. In 1947, he served as meteorological advisor for the Union of South African Government. Additionally, he was the U.S. commissioner for the Seattle World's Fair in 1961-1962, the chairperson of the National Fisheries Center and Aquarium Advisory Board for the U.S. department of the interior, and a member of the Advanced Commission for Armed Forces. He is credited with the research and development of meteorological equipment, radar and radio upper wind finding, spherics, and the development of meteorological instruments for measurements from aircraft in flight. His awards included a Decorated Legion of Merit Exceptional Civilian Service Medal from the U.S. Air Force, and a Patriotic Civilian Service Award from the U.S. Army. See Who's Who in Science from Antiquity to Present (Chicago, IL: Marquis Who's Who, Inc., 1968). Lyman Spitzer, Jr. (1914-1997) earned his B.A. and D.Sc. from Yale University (1935, 1958); Ph.D. from Princeton University (1938); D.Sc. from Case Institute of Technology (1960); and his LL.D. from Toledo University (1963). He was an instructor of physics and astronomy and an associate professor of astrophysics at Yale from 1946 to 1947. As a Charles A. Young Professor of Astronomy, he taught at Princeton and became the chairperson of the astrophysical sciences department and director of the observatory in 1947. Dr. Spitzer was the director of Project Matterhorn (1953-1961) and chairperson of the executive committee of the Plasma Physics Laboratory (1961-1966). He was a member of the National Academy of Sciences, American Academy of Arts and Sciences, American Philosophical Society, International Academy of Astronautics, and was the president of the American Astronomical Society. Dr. Spitzer received the Rittenhouse Medal (1957), NASA Medal (1972), Bruce Medal (1973), and Draper Medal (1974). He was the author of Physics of Fully Ionized Gasses (New York, NY: Interscience Publishers, 1956), Diffuse Matter in Space (New York, mogony, stellar atmospheres, and plasma physics. He also pioneered research on controlled thermonuclear fusion and in space astronomy. See Who's Who 1976-77: An Annual Biographical Dictionary (New York, NY: St. Martin's Press, 1976). Ernst Stuhlinger (1913- ) is a physicist who earned his Ph.D. at the University of Tbingen in 1936, and con- tinued research into cosmic rays and nuclear physics until 1941 while serving as an assistant professor at the Berlin Institute of Technology. He then spent two years as an enlisted man in the German army on the Russian front before being assigned to the rocket development center at Peenemunde, Germany. There he worked prin- cipally on guidance and control of rockets. After World War II, he came to the United States as part of Project Paperclip and worked with Wernher von Braun at Fort Bliss, Texas, and then at the Redstone Arsenal in Huntsville, Alabama. Transferred to the Marshall Space Flight Center in 1960, he was director of its space sci- ence laboratory from 1960 to 1968 and then its associate director for science from 1968 to 1975, when he retired and became an adjunct professor and senior research scientist with the University of Alabama at Huntsville. He directed early planning for lunar exploration and the Apollo telescope mount, which flew on Skylab and pro- duced a wealth of scientific information about the Sun. He also was responsible for the early planning on the high energy astronomy observatory and contributed to the initial phases of the space telescope project. His work included studies of electric propulsion and of scientific payloads for the Space Shuttle. See “Stuhlinger, Ernst," biographical file, NASA Historical Reference Collection. T Eldon Taylor (1929- ) served as President Carter's inspector general for NASA from 1979 to 1981. He was the first director of administration for the Virginia Center for Innovative Technology, and assistant director of admin- istration for the National Science Foundation from 1973 to 1979. Mr. Taylor was a Navy civilian from 1949 to 1959 (with time out for military service), and graduated from American University with a B.S. and M.S. in public affairs. He has earned several awards, including the William A. Jump Meritorious Award, NASA's Exceptional Service Award, the Environmental Protection Agency Special Achievement Award, and the National Science Foundation Distinguished Service Award. See “Taylor, Eldon,” biographical file, NASA Historical Reference Collection. Maj. Gen. Holger Toftoy (1903-1967) was a career U.S. Army officer, an expert in ordnance, and was responsible for bringing the German Rocket Team under the leadership of Wernher von Braun to the United States in 1945. He became commander of the Redstone Arsenal in Huntsville, Alabama, in 1954, and worked closely with von Braun's teams in the development of the Redstone and Jupiter missiles. In the aftermath of Sputnik 1 in 1957, he persuaded the department of defense to allow the launch of the United States' first Earth-orbiting satellite aboard the Jupiter missile and the result was the orbiting of Explorer 1 on January 31, 1958. He also held a number of other positions in the Army, such as head of the Rocket Research Branch of the Chief of Ordnance in Washington, DC, and com- mander of the Aberdeen Proving Ground in Maryland. He retired from the Army in 1960 with the rank of major general. See "Maj. Gen. Holger Toftoy Dies; Leader in U.S. Rocket Program,” New York Times, April 20, 1967, p. 41. Richard Tousey (1909-1997) received a Ph.D. in optical physics from Harvard University in 1933. He worked as a solar physicist at the Naval Research Laboratory for a number of years, leading the rocket spectroscopy branch of its space science division. Tousey specialized in vacuum ultraviolet spectroscopy and he designed a camera that the Skylab astronauts used to photograph the Sun. See Richard Tousey obituary, The Washington Post, April 16, 1997, p. B5, and "Tousey, Richard," biographical file, NASA Historical Reference Collection. Charles Townes (1915- ) was trained in physics at Duke University and specialized in the development of laser and maser technology. He first worked for the Bell Telephone Laboratories and, in 1948, joined the faculty of Columbia University, leaving there in 1961 to move to the Massachusetts Institute of Technology and on to the University of California. For his work on the maser, Townes received the Nobel Prize in 1964. See David E. Newton, “Charles H. Townes,” in Emily J. McMurray, ed., Notable Twentieth-Century Scientists (New York, NY: Gale Research Inc., 1995):2042-44. John W. Townsend, Jr. (1924– ) was the deputy director of the Goddard Space Center (1965–1968) and director (1987-1990). Additionally, he worked at the Naval Research Laboratory from 1949 to 1958, serving as branch head from 1955 to 1958. He has held several positions in various scientific fields, including deputy administrator of the 764

Environmental Sciences Services Administration (1968-1970), associate administrator of the National Oceanic and Atmospheric Administration (1970-1977), president of the Fairchild Space and Electronics Company (1977-1982), and president of the Fairchild Space Company (1983-1987). He also has been involved in the International Academy of Astronautics, NASA Advisory Council, National Academy of Engineering, National Research Council Space Applications Board, and the Office of Technology Assessment Advisory Board Panel on International Cooperation and Competition in Civilian Space Activities. He earned his B.A., M.A., and Sc.D. from Williams College. See "Townsend, John W., Jr.," biographical file, NASA Historical Reference Collection. V James Van Allen (1914- ) is a pathbreaking astrophysicist best known for his work in magnetospheric physics. Van Allen's January 1958 Explorer 1 experiment established the existence of radiation belts-later named for the scientist—that encircled the Earth, representing the opening of a broad research field. Extending outward in the direction of the Sun approximately 40,000 miles, as well as stretching out with a trail away from the Sun to approximately 370,000 miles, the magnetosphere is the area dominated by Earth's strong magnetic field. See James A. Van Allen, Origins of Magnetospheric Physics (Washington, DC: Smithsonian Institution Press, 1983); David E. Newton, “James A. Van Allen,” in Emily J. McMurray, ed., Notable Twentieth-Century Scientists (New York, NY: Gale Research Inc., 1995):2070-72. Wernher von Braun (1912–1977) was the leader of what has been called the "rocket team," which had developed the German V-2 ballistic missile in World War II. At the conclusion of the war, von Braun and some of his chief assistants as part of a military operation called Project Paperclip■came to America and were installed at Fort Bliss in El Paso, Texas, to work on rocket development and use the V-2 for high altitude research. They used launch facilities at the nearby White Sands Proving Ground in New Mexico. Later, in 1950, von Braun's team moved to the Redstone Arsenal near Huntsville, Alabama, to concentrate on the development of a new missile for the Army. They built the Army's Jupiter ballistic missile, and before that the Redstone, used by NASA to launch the first Mercury capsules. The story of von Braun and the "rocket team” has been told many times. See, as exam- ples, David H. DeVorkin, Science With a Vengeance: How the Military Created the US Space Sciences After World War II (New York, NY: Springer-Verlag, 1992); Frederick I. Ordway III and Mitchell R. Sharpe, The Rocket Team (New York, NY: Thomas Y. Crowell, 1979); Erik Bergaust, Wernher von Braun (Washington, DC: National Space Institute, 1976). W Gerry Wasserburg (1927-) earned his B.S., M.S., and Ph.D. from the University of Chicago, and has taught at the California Institute of Technology, University of Kiel, Harvard University, University of Bern, and the Swiss Federal Technical Institute. Primarily his research is in the fields of geology, geochemistry, and geophysics. His awards and recognitions include NASA's Group Achievement Award (Lunar Sample Analysis Planning Team, 1969), Arthur L. Day Medal (Geological Society of America, 1970), Medal for Distinguished Public Service (NASA, 1972), J. F. Kemp Medal for Distinguished Public Service (Columbia University, 1973), and Leonard Metal (Meteoritical Society, 1975). See “Wasserburg, Gerry," biographical file, NASA Historical Reference Collection. Alan Waterman (1892-1967) was a prominent physicist who served as director of the National Science Foundation and president of the American Association for the Advancement of Science. He received his Ph.D. from Princeton University. He was the deputy chief and chief scientist in the Office of Naval Research from 1931 to 1948. In 1964, he was sworn in as a consultant to NASA. See "Waterman, Alan," biographical file, NASA Historical Reference Collection. James Edwin Webb (1906-1992) was the second administrator of the National Aeronautics and Space Administration. Mr. Webb was educated at the University of North Carolina, where he received an A.B. in edu- cation 1928. He also studied law at George Washington University and was admitted to the Bar of the District of Columbia in 1936. President Harry S Truman asked Mr. Webb to serve as under secretary of state in the U.S. Department of State. When the Truman administration ended early in 1953, Mr. Webb left Washington for a position in the Kerr-McGee Oil Corporation in Oklahoma. James Webb returned to Washington on February 14, 1961, when he accepted the position of administrator of NASA. Under his direction, the agency undertook one of the most impressive projects in history, the goal of landing an American on the Moon before the end of the 765 decade through the execution of Project Apollo. After retiring from NASA, Mr. Webb remained in Washington, DC, serving on several advisory boards, including as a regent of the Smithsonian Institution. He died on March 27, 1992. For more information about James E. Webb see the 1995 biography published by the Johns Hopkins University Press, issued in the "New Series in NASA History." Written by W. Henry Lambright of Syracuse University, Powering Apollo: James E. Webb of NASA, emphasizes the leadership style and method of management Webb brought to complex organizational issues. Fred L. Whipple (1906- ) received his Ph.D. in astronomy from the University of California, Berkeley, and served on the faculty of Harvard University. He was involved in efforts in the early 1950s to expand public inter- est in the possibility of spaceflight through a series of symposia at the Hayden Planetarium in New York City and articles in Collier's magazine. He also was heavily involved in planning for the International Geophysical Year, 1957-1958. As a pathbreaking astronomer he pioneered research on comets. See Raymond E. Bullock, "Fred Lawrence Whipple," in Emily J. McMurray, ed., Notable Twentieth-Century Scientists (New York, NY: Gale Research Inc., 1995):2167-70. Z Harold Adelbert Zahl (1904-1973) earned his B.A., M.S., and Ph.D. from North Central College in Naperville, Illinois. He was a physicist for the U.S. Army from 1931 to 1966, where he was the director of research of the Electronics Laboratory, director of the Atmospheric Sciences Laboratory, and worked for the U.S. Electronics Command. In addition to authoring Electrons Away...or Tales of a Government Scientist (New York, NY: Vantage Press, 1968), he researched and published works regarding verification of wave particle dualism of atoms, and propagation of sound through the ocean, radar, and electron tubes. He developed the infrared detecting cell, tubes used in radar tube (i.e., the Zahl tube), and radar switching tubes. His decorations included the Department of the Army Decoration for Exceptional Civilian Service, Scientific Achievement Award from the Service Clubs of Long Island, Federal Business Association of New York Outstanding Civilian Award, and the Distinguished Alumnus award of North Central College. See Who's Who in Science from Antiquity to Present (Chicago, IL: Marquis Who's Who, Inc., 1968). 766

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