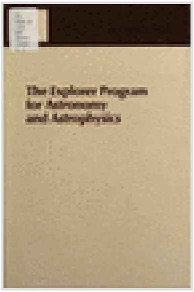


The Explorer Program for Astronomy and Astrophysics (1986)

Pages
59

Size
5 x 8

ISBN
0309123070

Committee on Space Astronomy and Astrophysics, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council

THE EXPLORER PROGRAM FOR ASTRONOMY AND ASTROPHYSICS

Committee on Space Astronomy and Astrophysics
Space Science Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council (U.S.),

NATIONAL ACADEMY PRESS
Washington, D.C. 1986

NOTICE: The project that is the subject of this document was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee that cosponsored the workshop were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

Frontispiece: The IRAS sky survey in the infrared (1983) showing many striking features of solar-system and extrasolar point and diffuse sources. Blue represents emission at 12 microns, green represents emission at 60 microns and red represents emission at 100 microns. The plot is in galactic coordinates, and shows the Milky Way (the bright yellow band in the figure) to be bright at 60 and 100 microns. Warm dust in the solar system (the sideways S-shaped blue curve in the figure) emits strongly at 12 microns. *Courtesy:* Infrared Processing and Analysis Center, Jet Propulsion Laboratory, California Institute of Technology.

Available from
Space Science Board
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

COMMITTEE ON SPACE ASTRONOMY AND ASTROPHYSICS

BLAIR D. SAVAGE, University of Wisconsin, *Chairman*
ERIC E. BECKLIN, University of Hawaii
JOSEPH P. CASSINELLI, University of Wisconsin
ANDREA K. DUPREE, Harvard-Smithsonian Center for Astrophysics
JAMES L. ELLIOT, Massachusetts Institute of Technology
WILLIAM F. HOFFMANN, University of Arizona
HUGH S. HUDSON, University of California, San Diego
MICHAEL JURA, University of California, Los Angeles
JAMES KURFESS, Naval Research Laboratory
STEPHEN S. MURRAY, Harvard-Smithsonian Center for Astrophysics
SAUL A. RAPPAPORT, Massachusetts Institute of Technology
ANTHONY READHEAD, California Institute of Technology
CRAIG L. SARAZIN, University of Virginia
NICHOLAS Z. SCOVILLE, California Institute of Technology
ADRIENNE PEDERSEN, BDM Incorporated
MARK E. WIEDENBECK, University of Chicago

RICHARD C. HART, *Executive Secretary*

Liaison Representatives

STEPHEN S. HOLT, Goddard Space Flight Center
BERNARD F. BURKE, Massachusetts Institute of Technology

SPACE SCIENCE BOARD

THOMAS M. DONAHUE, University of Michigan, *Chairman*
DON L. ANDERSON, California Institute of Technology
D. JAMES BAKER, Joint Oceanographic Institute
ROGER D. BLANDFORD, California Institute of Technology
JAY M. GOLDBERG, University of Chicago
DONALD HALL, University of Hawaii
DONALD M. HUNTEN, University of Arizona
WILLIAM KAULA, NOAA
HAROLD KLEIN, University of Santa Clara
STAMATIOS M. KRIMIGIS, Johns Hopkins University
ROBERT M. MacQUEEN, National Center for Atmospheric Research
CARL E. McILWAIN, University of California, San Diego
ROBERT PEPIN, University of Minnesota
CHRISTOPHER RUSSELL, University of California, Los Angeles
BLAIR D. SAVAGE, University of Wisconsin
J. WILLIAM SCHOPF, University of California, Los Angeles
JOHN SIMPSON, University of Chicago
DARRELL STROBEL, Johns Hopkins University
ANTHONY L. TURKEVICH, University of Chicago
RAINER WEISS, Massachusetts Institute of Technology

DEAN P. KASTEL, *Staff Director*

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

HERBERT FRIEDMAN, National Research Council, *Chairman*
CLARENCE R. ALLEN, California Institute of Technology
THOMAS D. BARROW, Standard Oil Company, Ohio (retired)
ELKAN R. BLOUT, Harvard Medical School
BERNARD F. BURKE, Massachusetts Institute of Technology
GEORGE F. CARRIER, Harvard University
CHARLES L. DRAKE, Dartmouth College
MILDRED S. DRESSELHAUS, Massachusetts Institute of Technology
JOSEPH L. FISHER, George Mason University
JAMES C. FLETCHER, University of Pittsburgh
WILLIAM A. FOWLER, California Institute of Technology
GERHART FRIEDLANDER, Brookhaven National Laboratory
EDWARD D. GOLDBERG, Scripps Institution of Oceanography
MARY L. GOOD, Allied Signal Corporation
J. ROSS MACDONALD, University of North Carolina, Chapel Hill
THOMAS F. MALONE, Saint Joseph College
CHARLES J. MANKIN, Oklahoma Geological Survey
PERRY L. McCARTY, Stanford University
WILLIAM D. PHILLIPS, Mallinckrodt, Inc.
ROBERT E. SIEVERS, University of Colorado
JOHN D. SPENGLER, Harvard School of Public Health
GEORGE W. WETHERILL, Carnegie Institution of Washington
IRVING WLADAWSKY-BERGER, IBM Corporation

RAPHAEL G. KASPER, Executive Director
LAWRENCE E. McCRAY, Associate Executive Director

FOREWORD

The Space Science Board's (SSB) Committee on Space Astronomy and Astrophysics (CSAA) prepared the following report in order to provide NASA with a strategy for proceeding with Explorer-class programs for research in space astronomy and astrophysics. With this report and its companion, *A Strategy for the Explorer Program for Solar and Space Physics* (National Academy Press, 1984), prepared by the Space Science Board's Committee on Solar and Space Physics (CSSP), the SSB has now completed its study of NASA's Explorer Program.

These two reports strongly endorse a vigorous Explorer Program, but are necessarily different in ways that reflect the needs of the respective disciplines. Solar and space physics requires direct access to a large volume of space and frequent opportunities in order to keep the science vital. Space astronomy also requires frequent access to space and often needs technologies (*i.e.*, those enabling accurate pointed observations) that are inherently costly and result in more expensive missions. The needs of these different areas of science require a flexible program to support many different approaches.

The great strengths of the Explorer Program—easy, frequent, and inexpensive access to space—have not been fully exploited in recent years. Although more advanced technologies and some scientifically ambitious missions have been developed within the program, the main reason for the loss of vigor of the Explorer Program has been the erosion of buying power by a budget that has not kept pace with inflation. The program could serve most of the requirements of the space physics, solar physics, and astronomy and astrophysics communities if NASA would make a strong effort to ensure the program proceeds expeditiously and if a major augmentation of the budget is provided. The CSSP and CSAA reports document in a convincing way that the health of space physics, solar physics, and astronomy and astrophysics requires a total Explorer budget of approximately $130 million (1986 dollars) per year ($80 million for astronomy and astrophysics and $50 million for solar and space physics).

Even in an era of space stations and Great Observatories, Explorers will play an important role in furthering the objectives of space physics, solar physics, and astronomy and astrophysics. They will continue to be the primary tool for exploring new regions or phenomena, a means of demonstrating new design concepts and hardware for scientific instruments, the bridge between sounding rocket/Spartan experiments and major missions, and an opportunity to develop the scientific research and engineering capabilities of individuals and organizations. We believe it is imperative that the tremendous potential of the Explorer Program to the United States space research effort not be lost—NASA must make the effort to revitalize the program and provide the necessary funding.

Thomas M. Donahue, Chairman
Space Science Board

PREFACE

In its first 25 years the Explorer Program has produced an outstanding record of discoveries that impact nearly all aspects of the scientific study of the Universe. However, looking to the future there are major problems within the Explorer Program. The number of Explorer flight opportunities is rapidly diminishing and an exceedingly long interval of time now passes between initial acceptance and the actual launch of an Explorer mission. Missions selected in 1974 will probably not fly until the early 1990s. Because of concern over the future viability of the program, the Committee on Space Astronomy and Astrophysics (CSAA) under the Chairmanship of Jacques M. Beckers began a study in November 1984 of NASA's Explorer Program in order to evaluate the future role of Explorer-class missions for astronomy and astrophysics. The CSAA Explorer study was chaired by Andrea K. Dupree and was charged with addressing the following points:

- The role of Explorers in astronomical research.
- Scientific objectives for Explorers.
- Cost, capability, and frequency of astronomy missions.
- Examples of possible missions.

- Selection process for new Explorers.
- Relation to other programs, *e.g.*, Spartans, Space Station, Space Observatories.

In our study of the Explorer Program for the past two years, we consulted many members of the space astronomy and astrophysics community and listened to presentations by scientists, project managers, and engineers to learn of their experiences and to profit from their advice. Draft versions of the CSAA Explorer report were discussed extensively at three meetings of the full CSAA between February 1985 and March 1986. In order to have a broad ranging discussion within the science community, draft versions of the report were presented and discussed at meetings of two NASA advisory committees (Astrophysics Management and Operations Working Group and Astrophysics/Relativity Management and Operations Working Group).

Our report was in preliminary draft form when the Space Shuttle Challenger exploded on January 28, 1986. Our Committee shares with the nation a deep grief over the loss of the seven exceptional people aboard that mission.

In the reassessment of the United States space program which is now occurring, it is very appropriate to consider how the Challenger disaster will influence the Explorer Program. In the short term (the next 4 years), it appears that launch opportunities for space science payloads will be severely limited. This will undoubtedly delay the launch of several Explorer missions. Since a vigorous healthy Explorer Program requires frequent and timely access to space, we hope there is a careful reevaluation of the most cost effective way to provide that access in the future.

Astronomy and Astrophysics Explorers have produced spectacular advances in our knowledge of the universe. Future Explorers currently in the queue will also certainly produce fundamental new knowledge. However, the rate of progress in the future will be greatly slowed unless there is a substantial augmentation in the funding of the Explorer Program.

The task of producing this report involved the help of many of our scientific and technical colleagues. Even though we cannot acknowledge all individually, we are grateful for their thoughtful contributions. We especially wish to acknowledge the assistance we received from NASA headquarters, particularly from C. Pellerin and E. Weiler. Richard Hart as Executive Secretary was an invaluable resource and source of support. Stephanie Deeley of the Center for Astrophysics produced a superb manuscript.

Andrea K. Dupree, Chairman
CSAA Explorer Report

Blair D. Savage, Chairman
Committee on Space Astronomy and
Astrophysics

CONTENTS

I. EXECUTIVE SUMMARY

INTRODUCTION

The Explorer Program has established an outstanding record of scientific accomplishments in a variety of space science fields including astronomy and astrophysics, space plasma physics, and solar physics. This report reviews the accomplishments and continuing promise of the Explorer Program for Astronomy and Astrophysics. It describes the unique character of Explorer opportunities and presents an assessment of the funding requirements necessary to maintain an effective scientific program for astronomy and astrophysics. The needs of the solar and space physics community have been addressed in a previous report (*A Strategy for the Explorer Program for Solar and Space Physics,* National Academy Press, 1984).

Experiments in the Explorer line offer well-defined, problem-oriented opportunities to achieve observations and measurements in space. Continuity and stability of the Explorer budget line enable reasoned scientific programs to be developed and carried out. The success of the program stems also from the flexible mix of Principal Investigator (PI) class instruments and of moderate experiments using both free-flying spacecraft and "piggyback" instruments. Guest Observer programs have captured individual talents and the imagination of many hundreds of astronomers per year. Explorers also provide the opportunity for free-flying spacecraft to be located in regions of space that are optimum for the scientific goals.

Of great concern is the drastic decrease in the rate of Explorer launches: from three to four per year in the 1960s to less than one per year in the 1980s for all of the space science disciplines. This decline can be attributed to several causes: increasing weight and sophistication of instruments and spacecraft, extended development phases, unanticipated technical problems, and a budget ravaged by inflation, which causes extended study and development phases. Some of these causes highlight the true success of the program. Scientific research naturally evolves to face the unanswered questions. Many of the simple measurements have been made. As we build up our understanding of the universe, we address more difficult problems, and this can lead to more sophisticated (and costly) experiments.

The Committee on Space Astronomy and Astrophysics (CSAA) undertook this study to evaluate and comment on the role of Explorers in astronomy and astrophysics. The scientific guidelines remain those stated in the report of the Astronomy Survey Committee, *Astronomy and Astrophysics for the 1980's* (National Academy of Sciences, 1982).

Broadly-based consultations with scientists, engineers, and administrators have helped the committee to enumerate many considerations that can result in a more effective Explorer Program for Astronomy and Astrophysics.

RECOMMENDATIONS

There is no doubt that the Explorer Program has resulted in outstanding scientific discoveries and continues to contribute in a vital way to the progress of space research in astronomy and astrophysics. Our discussions have led to five recommendations to enhance the effectiveness of this program in the coming decades.

1. Astronomy and Astrophysics Explorers have produced spectacular advances in our knowledge of the universe. Major Explorer missions that are approved for future flight, such as the Cosmic Background Explorer (COBE),

Extreme Ultraviolet Explorer (EUVE), and X-ray Timing Explorer (XTE) are likely to lead to similar advances. These missions include survey/discovery missions such as *Uhuru* and the Infrared Astronomical Satellite (IRAS), and missions devoted to directed detailed study such as the International Ultraviolet Explorer (IUE) and XTE. The Astronomy Survey Committee has identified many Explorer opportunities, and in response to the 1986 Dear Colleague Letter, this committee expects additional Explorer concepts that have similar promise for the future.

Therefore, we recommend that Astronomy and Astrophysics Explorers be continued as a vital part of the NASA space astrophysics program. To allow important scientific goals to be achieved in a reasonable time, an allocation of approximately $80 million dollars per year (FY 1986 dollars) for Astronomy and Astrophysics Explorers within the total Explorer budget is required. We recommend that the Explorer budget be augmented sufficiently to accommodate this amount.

2. The era of the Space Shuttle and Space Station, and the increased worldwide activity in space, create new types of Explorer opportunities in addition to the traditional launches of dedicated Explorer spacecraft missions. These new opportunities include retrieval and refurbishment of spacecraft for dedicated missions, use of space station related carriers such as *Eureca,* (European Retrieval Carrier) and provision of instruments for foreign missions. The latter two can increase the frequency of opportunity so important to the Explorer concept. Reuse or duplication of spacecraft can lower the costs of spacecraft that are now a substantial fraction of a mission budget.

   Astronomy and Astrophysics Explorer missions should include a mix of dedicated spacecraft, instruments on refurbished spacecraft, and instruments on foreign missions.

3. The record of the past and plans for the near future testify to the high quality of innovative science that is achieved by peer-selected Explorer science.

   Open competition for selection of new Explorer concepts should occur frequently. These investigations should continue to be selected on the basis of peer review, based on scientific excellence, timeliness, and cost-effectiveness. Part of the Explorer budget should be used, as it now is, to effect small, timely projects that should be subject to the scrutiny of standing committees in the context of all Explorer options and other flight opportunities.

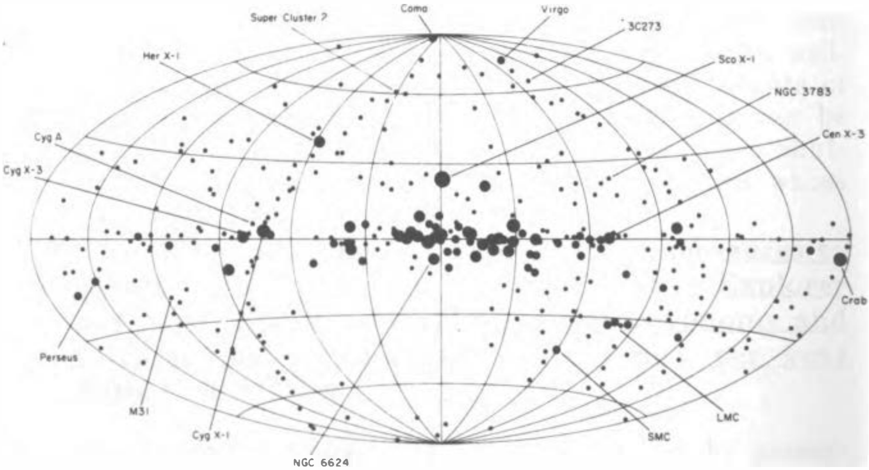
4. Observations from space form an integral part of contemporary astrophysics. Frequent and timely access to space opportunities represents an essential aspect of the Explorer Program—a characteristic that allows the community to address forefront scientific questions with well-defined experiments, and to attract the many talents of scientific researchers and students. Experiments can be launched by expendable vehicles and by the Space Shuttle. Missions can also be designed for platforms whose payloads are replaced while in orbit.

   We recommend that NASA take measures to ensure regular access to space for future Explorer payloads. For the scientific goals of astronomy and astrophysics, one Explorer opportunity per year must be available.

5. The Explorer Program can serve science best by permitting international cooperation in the most flexible manner. For programs of moderate scope, the inclusion of international partners may help to enhance scientific return and reduce the cost to the Explorer Program while maintaining the desired launch frequency.

   We encourage NASA, in collaboration with the international science community, to continue to

take advantage of the unique features of the Explorer Program to foster cooperative scientific missions with space agencies of other nations.



SAS-1 (*Uhuru*): A remarkable achievement of an astronomical sky survey was the *Uhuru* survey in 2-6 keV x-radiation (1970-1971) showing a profusion of point cosmic x-ray sources.

II. THE ROLE OF EXPLORERS IN ASTRONOMY AND ASTROPHYSICS

GOALS OF THE EXPLORER PROGRAM

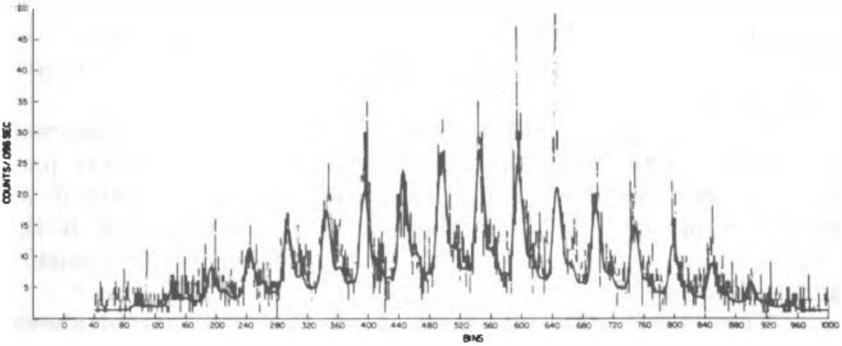
The Explorer Program has provided the astronomy and astrophysics community with small and moderate-sized missions for a remarkable variety of mission types. Explorer spacecraft have been used as a generally inexpensive resource to survey cosmic objects in new spectral regions or to carry out intensive study of more narrowly defined scientific programs. Explorer science has been achieved in several ways ranging from Principal Investigator (PI) instruments to moderate experiments open to a Guest Observer community in part or in total. Explorers represent scientific initiatives that are not large enough to justify a major new start for NASA. Although about 70 NASA Explorer spacecraft have been built and launched since the first Explorer launch in 1958, only eight of these Explorer missions were dedicated to astronomy and astrophysics. However, this handful of well-chosen Explorers has created enormous impact on the scientific course of astrophysics. We shall demonstrate the scientific achievements in Section III. In addition, if adequately funded, the Explorer Program can complement the execution of the scientific programs of NASA and the community in various ways by providing the following:

1. a modestly scaled option for scientific research,
2. a quick response to new scientific opportunities,
3. an extended observing period,
4. access to regions of space optimum for astronomical observations,
5. hands-on experience for university researchers and students,
6. international collaborations,
7. a first step to define and guide the requirements for major missions, and
8. complementarity and extension of the science of major missions.

These are laudable and achievable goals, but to the frustration of all space scientists, the frequency of flight opportunities in the Explorer line has diminished substantially. In the 1960s, rates of launch were three to four per year. In the late 1970s this figure was reduced to less than one per year. This rate of less than one Explorer per year for all space science disciplines is the rate we face in the 1980s. Moreover, the time elapsed from selection of an Explorer mission to its launch now exceeds 15 years.

In part, these problems result from the larger sizes of recent Explorer spacecraft. In astronomy and astrophysics, more complex instruments are frequently required to continue with detailed study after the first exploratory measurements. Also, the funds allocated for the Explorer Program have not kept pace with inflation. Allowing for inflationary growth since 1965 would lead to a sum of $87M for the Explorer line, when in fact it now stands at $48.2M in FY 1986.

We are deeply worried that the frequency of flight opportunities has fallen below the critical level necessary to attract and ensure participation by the best and most imaginative scientific groups. The lead time for Explorer experiments is now so long and the likelihood of timely flight so low that large segments of the community are discouraged. The astronomical community has urged, through CSAA, the Space Science Board



***SAS-1 (Uhuru)*:** **Discovery of one of the first x-ray pulsars (Cen X-3) by *Uhuru*, the first Small Astronomical Satellite. These systems consist of neutron stars in close binary companionship with other stars that can supply the enormous x-ray luminosity of the system via mass transfer to the neutron star. The pulsations seen here are at the rotation period of the neutron star, 4.84 s.**

(SSB), and, most recently, the Astronomy Survey Committee, a major influx of funds for the Explorer Program to ensure a minimum healthy level of flight opportunities in astronomy (*e.g.*, one astronomy and astrophysics Explorer opportunity every year). Budgetary restrictions have thus far precluded a major augmentation in the Explorer line and in fact, it was reduced in FY 1986. As a result, the queue of experiments awaiting flight is long and there appear to be no new dedicated opportunities for flights prior to 1991. This backlog of waiting programs has profound implications: creative new ideas may become stifled for want of opportunity; resources committed to maintaining programs waiting for initiation may be wasted; international endeavors cannot be encouraged; the energetic scientists required to design and operate the instruments may be difficult to find if the lack of creative new endeavors causes them to abandon the field; and the intellectual framework for training new scientists will be in serious jeopardy. The Explorer Program has provided an opportunity for young research scientists to develop their talents. Their activities include actual hands-on experience with flight hardware, or careful reduction and theoretical analysis of measurements obtained with Explorer missions. Long gaps between Explorer opportunities, and stretched-out schedules will compromise the education and training of this new generation of scientific and technical researchers.

It is urgent that this situation be addressed immediately—the programs that have been waiting for the past several years, and new concepts, must be initiated soon if we are to maintain a healthy space science program, and if the United States wishes to continue to be a leader in space science and technology.

This report addresses some of the problems stated above, presents an assessment of critical areas, and recommends a philosophy and guidelines to increase the productivity of the Explorer missions.

DEVELOPMENTAL COMPONENTS OF SPACE ASTROPHYSICS

The intellectual and technological developments of space astrophysics contain four components in a synergistic partnership.

- In the discovery component we find qualitatively new phenomena as a direct consequence of a technological advance that allows a wholly new type of observation. Such technological advances may permit observations in a new wavelength range or with greatly improved spectral resolution, sensitivity, angular resolution, or timing ability. Suborbital programs (sounding rockets, balloons, and aircraft) have usually played leading roles in this activity. In many spectral regions astrophysical research has accomplished the discovery measurement, but the EUV and submillimeter spectral regimes still have a large component of discovery.
- In the survey component, long duration flight experiments are used to survey the whole sky at moderate sensitivity

in order to catalog the number of each type of source in order to learn the range of phenomena in the universe, in what environments the sources are located, and what their evolutionary status and physical properties might be from comparison with observations at different wavelengths. In their own individual ways, specific Explorers have played this role for cosmic rays, gamma rays, x rays, ultraviolet, and the infrared. A future Explorer, EUVE, is expected to play this role for the extreme ultraviolet. The only remaining gap that cannot be accomplished through ground-based observations is the submillimeter wavelength interval that another future Explorer, COBE, can partially fill.

- Once the different types of sources are located and identified and some of their interesting properties recognized, one can design space missions for specific, detailed studies, the third component in space astrophysics. Such missions will typically emphasize one or several of the following: high sensitivity, high spectral resolution, high timing precision, or high angular resolution. With the greatly enhanced capability in one or more of these areas, such missions can determine the physical properties of the interesting astrophysical objects in great detail and thus begin to answer the major questions of astrophysics and also discover new phenomena for analysis. None of the space missions in this third component is now being built, although XTE is in an instrument study phase awaiting authority to begin development.
- The observatory component, represents permanent facilities in space built to accommodate many focal plane instruments, each with extraordinary sensitivity, spectral resolution, timing precision, and angular resolving power. These observatory-class facilities are designed for periodic refurbishment with new focal plane instruments at the forefronts of their fields. Each facility services a mature subdiscipline within astrophysics, consisting of a large number of users who will propose, as Guest Investigators, to obtain data for their programs. One of these observatory-class facilities, the Hubble Space Telescope (HST), is nearly ready to be launched, and another, the Gamma Ray Observatory (GRO), is at an advanced stage of construction. Others, the Advanced X-ray

Astrophysics Facility (AXAF), the Space Infrared Telescope Facility (SIRTF), and the Large Deployable Reflector (LDR), are high priority major missions endorsed by the Astronomy Survey Committee.

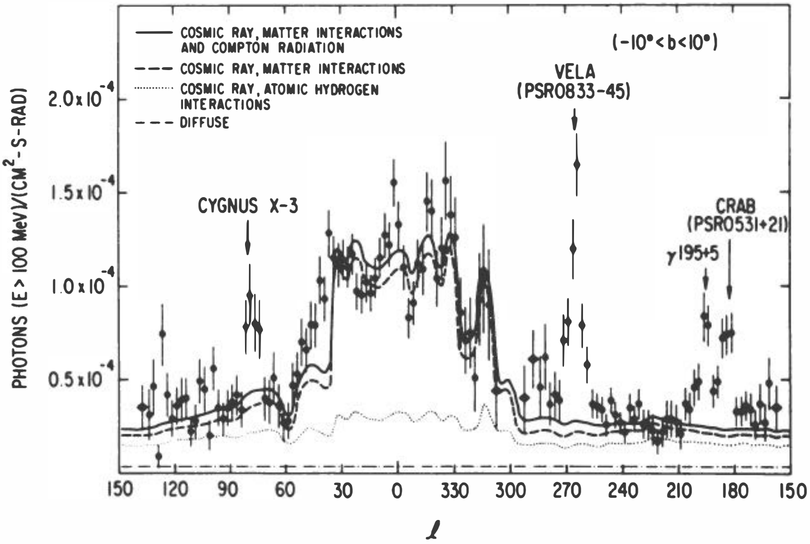
While each of these components is necessary, this report stresses the contributions to the overall program that can be accomplished with Explorer missions. Explorers are the vehicle of choice for two of these components: surveys and specific studies.

RELATION TO OTHER FLIGHT OPPORTUNITIES

The NASA program now provides opportunities for space research through a broad range of flight programs, ranging from suborbital vehicles through long duration, observatory-class spacecraft. The Explorer Program plays a vital role in the mid-region of this spectrum, providing extended duration exposure for small to moderate size instruments aboard dedicated free flying spacecraft. It has also provided access to special orbits which are dictated by scientific objectives. Examples include a halo orbit about the L1 libration point in the Earth-Sun system, ISEE; geosynchronous orbit, IUE; and polar Sun-synchronous orbit, IRAS.

Another key aspect of the Explorer Program is its level-of-effort character, which has had positive results: very substantial scientific returns at a modest cost and a relatively rapid response to new scientific opportunities including international efforts for small instruments. This feature of the program has an even greater importance for astronomy and astrophysics as we enter the era of large space observatories. The infrequency and uncertainty of new start opportunities would otherwise preclude the initiation of moderate but scientifically important missions. Level-of-effort programs do have a negative aspect as well—the delay and stretching out of all but the smallest missions.

In this new era of the Space Station, the Explorer Program, with its high degree of scientific productivity, might well serve as a model for future level-of-effort programs to utilize the Station and associated platforms for carrying out small, timely experiments.



***SAS-2*: Comparison of γ-ray brightness of the galactic plane with the distribution of diffuse matter, as represented by several model lines. Discrete sources as well as the diffuse galactic structure appear at different galactic longitudes, with a broad, major excess around the galactic center (ℓ = 0).**

III. ACCOMPLISHMENTS OF ASTRONOMY AND ASTROPHYSICS EXPLORERS

Eight Explorer missions pursued mainly astronomical goals. Many cosmic-ray and gamma-ray experiments were carried on Explorers devoted to other research disciplines. Explorer activities have also provided for international cooperation in spacecraft launches and the inclusion of U.S. x-ray instruments on ANS and Ariel-5. These past and planned future Explorer astrophysics missions are listed in Table 1.

The major accomplishments of these missions have substantially enlarged our understanding of practically every observable quantity in astronomy and astrophysics from radio astronomy to infrared, ultraviolet, x-ray, γ-ray, and cosmic-ray physics. A brief summary of scientific highlights from the astronomy Explorers follows, and many results illustrate this report.

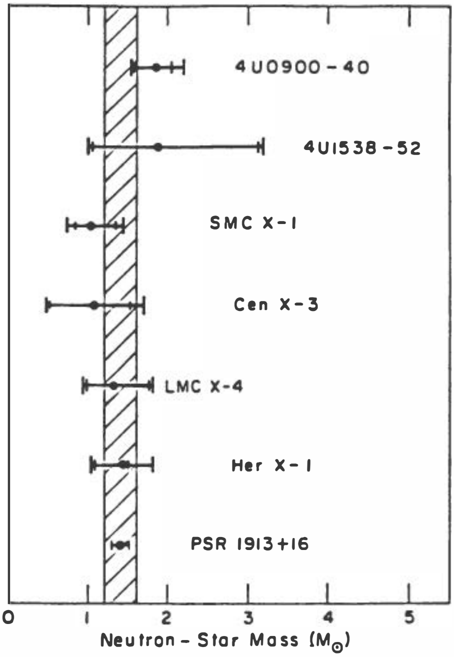
EXPLORER 11: GAMMA-RAY ASTRONOMY

Explorer 11, the first astronomical satellite, carried a directional detector designed to search for high energy gamma rays from the decay of neutral pions produced in the interactions of cosmic-ray nuclei with interstellar matter. Thirty

TABLE 1
ASTROPHYSICS EXPLORERS

Sequence	PAST MISSIONS	Date of Launch*
	Dedicated Astrophysics Missions	
1. Explorer 11	γ-Ray Astronomy	1961
2. Explorer 38	RAE-1: Radio Astronomy	1968
3. Explorer 42	SAS-1: X-Ray (*Uhuru*)	1970
4. Explorer 48	SAS-2: γ-Ray	1972
5. Explorer 49	RAE-2: Radio Astronomy	1973
6. Explorer 53	SAS-3: X-Ray	1975
7. IUE	International Ultraviolet Explorer	1978
8. IRAS	Infrared Astronomy Satellite	1983
	Participation in Other Missions	
1. IMP Series	Cosmic-Ray Experiments	1963-1973
2. Ariel 5	X-Ray Monitor	1974
3. ANS	X-Ray Proportional Counters	1974
4. ISEE-3	Cosmic-Ray and Gamma-Ray Experiments	1978
	FUTURE MISSIONS	
	Dedicated Astrophysics Missions	
1. COBE	Cosmic Background Explorer	1989
2. EUVE	Extreme Ultraviolet Explorer	1990
3. XTE	X-Ray Timing Explorer	1991
	Participation in Other Missions	
1. ROSAT	High Resolution Imager: Roentgen Satellite	1987
2. HNC	Heavy Nuclei Collector on Long Duration Exposure Facility	1987
3. CRRES	Cosmic-Ray Isotope Studies: Combined Release/Radiation Effects Satellite	1987

*** Launch dates for future missions are listed as they were planned prior to the interruption of Shuttle launches. Delays of at least two years, and in many cases significantly longer, are likely.**



SAS-3: Masses of neutron stars observed via their x-ray emission by SAS-3 (upper six) and via radio emission (the binary pulsar PSR 1913+16). The hatched band shows the range of masses expected from theoretical considerations of neutron-star formation, namely, 1.2 - 1.6 $M_\odot$.

events with possible gamma-ray signatures were recorded from the sky, and their rate of occurrence implied a firm upper limit on the intensity of cosmic gamma rays. This measurement disproved one version of the steady state theory of cosmology whereby nucleon-antinucleon pairs were assumed to be continuously created everywhere so as to maintain a constant density in the expanding universe.

EXPLORER 38: RAE-1

Radio Astronomy Explorer 1 (RAE-1), the first spacecraft designed specifically for radio astronomical studies, provided measurements over the frequency range 200 kHz to 9.2 MHz. Although the most extensive results from this mission were directed towards solar system astronomy and space plasma physics of the terrestrial magnetosphere, observations were made of galactic sources. Continuum background maps at frequencies of 4 and 6 MHz defined the distribution of the ionized component of the interstellar medium. Cosmic noise background spectra measured down to 0.5 MHz provided new estimates of the interstellar flux of cosmic rays, of magnetic fields in the galactic halo, and of the nature of radiation from distant extragalactic radio sources.

EXPLORER 42: SAS-1 (*UHURU*)

The launch of *Uhuru* (Small Astronomy Satellite: SAS), marked the first of the small satellites devoted to x-ray astronomy. It provided the first comprehensive sky survey in x rays and discovered several hundred galactic and extragalactic sources. Positions of these sources were measured with sufficient accuracy to enable identifications of optical counterparts. *Uhuru* also discovered pulsating x-ray stars in binary systems that are rotating, accreting, magnetized neutron stars, and unique temporal variations in Cygnus X-1 supporting the idea that Cygnus X-1 is a black hole in a close binary system. Extragalactic sources revealed variable x-ray emission from active galactic nuclei. Hot intergalactic plasma was found in certain clusters of galaxies with a total mass comparable to the total visible mass of the galaxies in the cluster.

EXPLORER 48: SAS-2

The second Small Astronomical Satellite (SAS-2), carrying a γ-ray telescope, confirmed the discovery of galactic and extragalactic gamma rays by the Orbiting Solar Observatory 3 (OSO-3), and mapped the intensity of high-energy gamma rays over $\sim$ 60 percent of the sky including most of the galactic plane. The distribution of γ-ray emission appeared generally correlated with galactic structural features, including spiral arm segments, as expected for cosmic-ray interactions with the interstellar gas. The uniformity measurements of diffuse γ-radiation clearly eliminated the galactic halo as the primary source. The intensity, uniformity, and energy spectra when combined seem to limit the possible origins to two: namely, active galaxies or matter-antimatter interactions at the boundaries of superclusters of galaxies in a baryon symmetric universe. Observations of some identified point sources showed pulsations or variability; in addition optically unidentified strong γ-ray sources were discovered.

EXPLORER 49: RAE-2

The second spacecraft dedicated to observations at radio frequencies 25 kHz to 13 MHz, the RAE-2 was launched into lunar orbit to reduce contamination from terrestrial radio emissions. Its orbit resulted in repeated lunar occultations of the Earth providing the welcome shielding of Earth's emissions and enabling galactic measurements to be made without interference. New measurements of the nonthermal galactic radio spectrum at frequencies below 10 MHz and survey maps of the spatial distribution of the low frequency galactic emission were obtained. The lowest frequencies allowed construction of a coarse picture of the local interstellar medium and its magnetic field in the immediate solar neighborhood.

EXPLORER 53: SAS-3

SAS-3 was an x-ray observatory spanning the energy range from 0.1 to 50 keV. Among its results were the discovery and analysis of the Rapid Burster and many other new x-ray burst sources. The observations led to the conclusion that a burster is a weakly magnetized neutron star accreting matter from a low mass companion, and to the identification of two types of x-ray bursts of which one is caused by fluctuations in the accretion flow, and the other by thermonuclear flashes in material accumulated on the neutron star surface. Timing studies of binary x-ray pulsars, including several discovered with SAS-3, yielded numerous precise orbit determinations and strong evidence that the masses of the neutron stars in such systems all lie within a narrow range around the Chandrasekhar mass limit for white dwarfs. Position determinations of over 60 galactic and extragalactic x-ray sources led to more than 40 new optical identifications including a nearby quasar, the hot white dwarf HZ43, and the first counterpart of an x-ray burster. An all-sky survey of the soft (0.1-0.3 keV) x-ray background provided evidence that a substantial portion originates in sources beyond the neutral hydrogen of the galactic disk and may be thermal emission from the galactic halo.

With SAS-3 a Guest Observer program was initiated for Explorers. This program allowed scientists, other than the Principal Investigator's team, to perform observations with the satellite. The Guest Observer program signaled the beginning of a rewarding new phase in space research with Explorers.

INTERNATIONAL ULTRAVIOLET EXPLORER

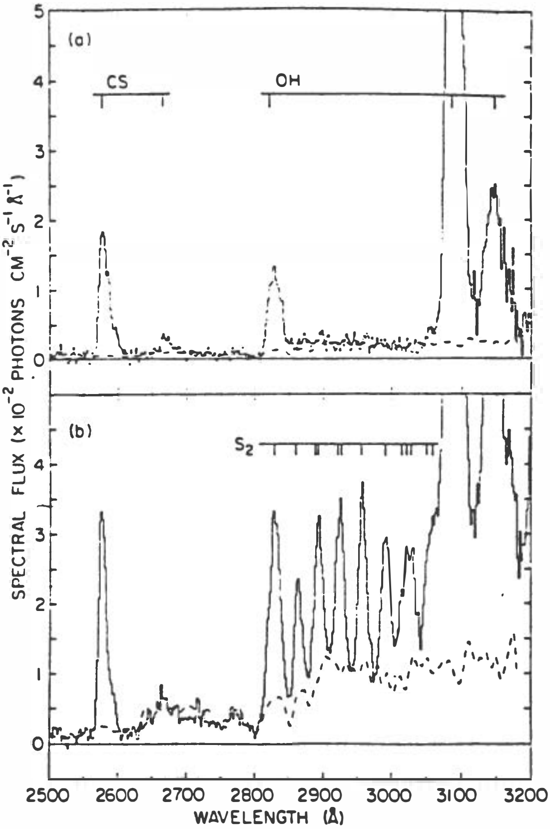
The International Ultraviolet Explorer (IUE) containing a small (0.45m diameter) ultraviolet telescope and spectrograph in geosynchronous orbit was built by NASA, the European Space Agency (ESA), and the Science and Engineering Research Council (SERC) of the United Kingdom. The observing time and spacecraft control are shared by the sponsoring agencies. NASA assigns two-thirds of the observing time; ESA/SERC scientists are allocated one-third. All of the observing time is allocated by peer review to Guest Observers forming a large international scientific community. About 210 programs are accepted by NASA alone each year; most of these programs involve several researchers. ESA/SERC additionally accepts many proposals for their observing time.

Since launch in 1978, the IUE continues to produce ultraviolet spectra of solar system, galactic, and extragalactic objects. Scientific programs are varied. Spectra from IUE have revealed a hot halo surrounding our galaxy and variability ascribed to different regions within active galactic nuclei. Observations of stars have demonstrated that winds and mass loss exist in practically every kind of star and have led to the discovery of accretion disk phenomena connected with compact objects. A comprehensive picture of magnetic activity evidenced by chromospheres, coronae, and extended atmospheres has been developed for large numbers of cool stars. Study of comets revealed new molecules; spectral observations of Comet Halley complemented the imaging from an international fleet of spacecraft and confirmed the source of ultraviolet emissions discovered by *Pioneer Venus*. Planetary aurorae associated with Jupiter, Saturn, and Uranus have been monitored.

INFRARED ASTRONOMICAL SATELLITE

The IRAS mission launched into polar sun-synchronous orbit was the result of a cooperative effort among the United States, the Netherlands, and the United Kingdom. IRAS made a survey of the entire sky at wavelengths of 12, 25, 60, and 100 μm. The primary products of the mission were a catalog of 245,000 point sources (stars, galaxies, and star formation regions) and a set of 212 images covering the entire sky with 2 arc minute resolution in the four wavelength bands. This catalog has been widely distributed to astronomy research centers, and more detailed study is now possible largely through a Guest Observer program comprising peer-reviewed proposals.

Studies of the data show that a significant number of nearby dwarf stars have a far infrared excess due to an extended disk or shell of solid material orbiting around and heated by the central star. This solid material is believed left over from the star formation process and represents protoplanetary material. Very small amounts of warm interstellar dust ("infrared cirrus") have also been discovered that can be used to trace out the local interstellar matter, to investigate the



***IUE*:** **Discovery of the molecule S_2 in the nucleus of comet IRAS-Araki-Alcock in 1983 (spectrum in lower panel). The upper panel shows the spectrum measured away from the comet nucleus; the broken lines denote the solar spectrum. The IUE has been one of the most productive of all astronomical satellites. The targets of IUE range from solar-system objects, such as this comet discovered by IRAS, to active galactic nuclei and quasars.**

dust-to-gas ratio, and define extinction-free areas in the sky. Stars of one solar mass or less have been revealed in the process of formation in nearby molecular clouds such as Taurus. Some 20,000 spiral galaxies were detected by IRAS. Many of these emit 5 to 1,000 times more energy in the infrared than at visual wavelengths. Some of these are galaxies harboring recent episodes of star formation ("starburst" galaxies), others may emit copious amounts of infrared radiation due to the presence of dust-embedded active nuclei. IRAS has also contributed significantly to the study of comets, asteroids, and dust within the solar system.

ASTROPHYSICS EXPERIMENTS ON OTHER MISSIONS

In addition to the Explorers that were devoted predominantly to astronomy and astrophysics, a number of astrophysics experiments have been carried out aboard Explorers that concentrated on other areas of space research.

1. *Cosmic-Ray Research*

Cosmic-ray investigations provided some of the earliest astrophysics results from the Explorer Program. A series of experiments carried aboard Interplanetary Monitoring Platforms (IMP) 1 through 8 (designated Explorers 18, 21, 28, 34, 41, 43, 47 and 50, respectively) made fundamental contributions to the study of cosmic ray spectra and composition. In the 1960s they demonstrated that the relative abundances of major elements are similar in galactic cosmic rays and in solar system matter, leading to the conclusion that the relativistic charged particles that permeate the galaxy are formed by normal processes of stellar nucleosynthesis. The most recent experiments have resolved the individual isotopes of some of the elements and have found significant excesses (relative to solar system matter) of neutron rich isotopes of the elements neon, magnesium, and silicon. These excesses indicate the possibility of regions of the galaxy with sizable metallicity enhancements or, alternatively, suggest a connection between cosmic ray injection and objects with peculiar surface abundances, such as Wolf-Rayet stars. Experiments aboard the IMP satellites discovered the low energy "anomalous component" of cosmic rays, now widely believed to be a population of particles accelerated from the local interstellar gas, and they demonstrated that this material does not contain the products of nuclear fragmentation that are characteristic of galactic cosmic rays. Explorer-borne experiments also measured the abundances of several long lived radioactive isotopes, which were used as "clocks" to establish that cosmic rays are confined by the galactic magnetic field for approximately 10 million years.

2. *Gamma-Ray Research*

Gamma-ray detectors were carried on several satellites of the IMP series and made fundamental discoveries concerning the surprising gamma-ray bursts. IMP-6, with detectors sensitive to the 0.1-1 MeV energy range provided the first verification of the gamma-ray burst phenomenon and obtained the first spectral measurements of gamma-ray bursts. Instruments on IMP-7 measured the spectra of about 25 gamma-ray bursts and demonstrated their similarity when averaged over the burst duration. ISEE-3 also carried instruments for the study of cosmic gamma-ray bursts. These instruments, used separately and in conjunction with experiments carried by an international network of spacecraft, made important contributions to the study of burst source spectra and locations.

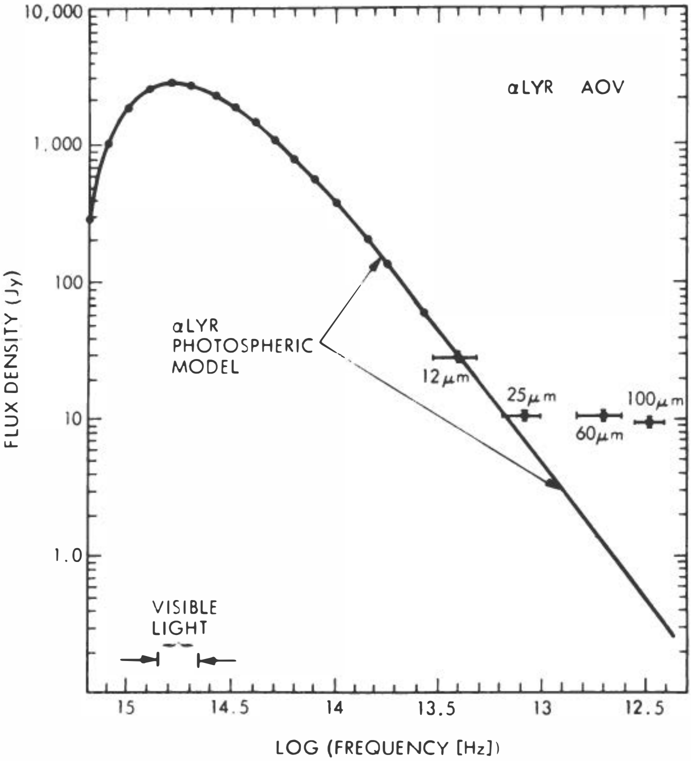
IV. CURRENT AND FUTURE ASTRONOMY AND ASTROPHYSICS EXPLORERS

THE CURRENT PROGRAM

The Announcements of Opportunity (AO) 6 and 7 issued in 1974, and selections in the mid-1970s, led to most of the current Explorers in the queue. Three astronomy missions are still waiting to be completed and launched: the Cosmic Background Explorer (COBE), the Extreme Ultraviolet Explorer (EUVE) and the X-Ray Timing Explorer (XTE). These missions are discussed below along with other projects now being funded under the Explorer line.

1. *Cosmic Background Explorer*

The COBE, which is under construction and expected to be ready for launch in 1989, is designed to make a substantial improvement in our knowledge of the condition in the universe at large red shifts. The focus of the mission is to study the spectrum, intensity, and isotropy of the primeval cosmic background radiation at wavelengths longer than that of the 3 K black body radiation maximum (at 1 mm), and to detect or set stringent limits on the universal radiation energy density at shorter wavelengths—radiation emanating from distant sources but at later times than the primeval fireball. This mission will



***IRAS*: A protoplanetary particle shell around the A0 star Vega (α Lyr). The excess over the photospheric continuum at low frequencies indicates the existence of a cool (80 K) shell concentrated some 80 Astronomical Units from the star.**

provide (a) freedom from atmospheric opacity, emission, and fluctuations in the emission, (b) full sky coverage with a single complement of instruments, (c) a benign and controlled thermal environment to reduce systematic errors, (d) the ability to perform absolute primary calibration in flight without the necessity of windows to avoid condensation of the atmosphere on calibrators and instruments, and (e) sufficient time both to perform tests for systematic errors and to gain the increase in sensitivity permitted by extended observation time.

COBE will map the spectrum and the angular distribution of diffuse radiation from the universe over the entire wavelength range from 1 μ to 1 cm. It will carry three instruments: a set of Differential Microwave Radiometers operating at 31.4, 53, and 90 GHz (1, 0.6, 0.3 cm respectively); a Far Infrared Absolute Spectrophotometer covering 1 to 100 cm^{-1} (1 to 0.01 cm); and a Diffuse Infrared Background Experiment covering 1 to 300 μ (10^{-4} to 0.3 cm). They will use the ideal space environment, a one year lifetime, and standard instrument techniques to achieve orders of magnitude improvements in sensitivity and accuracy, providing a fundamental data base for cosmology. The instruments are united by common purpose as well as by similar environmental and orbital requirements. The data from all three experiments will be analyzed together, to distinguish nearby sources of radiation from the cosmologically interesting diffuse background radiations.

2. *Extreme Ultraviolet Explorer*

EUVE, an approved mission, will survey the whole sky in several filter pass bands between 80 and 900 Å. The payload also includes three spectrometers which will be used to carry out spectroscopic observations of brightest sources; the bandpass covered is 80-700 Å with a resolving power of $\lambda/\Delta\lambda \gtrsim 100$. Until recently, the extreme ultraviolet spectral range was presumed to be of limited interest because the interstellar medium was expected to block passage of radiation in these wavelengths. However, recent discoveries have shown that the very local interstellar medium is partially ionized, and the density of neutral species is quite low (10^{-2} to 10^{-3} particles per cm^3) in some directions. This low density extends for considerable distances and the interstellar medium in general is very patchy. A number of stellar objects were detected at extreme ultraviolet wavelengths by an experiment on the Apollo-Soyuz mission, by subsequent rocket experiments, by the *Voyager* spacecraft, and by the European X-Ray Astronomy Satellite (EXOSAT) mission. Hot white dwarfs, cool stars, binary systems, cataclysmic variables, some planets, the interstellar medium and some extragalactic sources should be observable by EUVE. The EUVE spectrometer will be available to astronomers on a Guest Observer basis.

3. *X-Ray Timing Explorer*

The XTE, to be launched about 1992, will be devoted to temporal studies and broadband spectroscopy of compact x-ray sources over the energy range 1 to 200 keV. The experiments will feature a large photon collection area and an all-sky pointing capability with a complement of three instruments: a l-m^2 effective area xenon proportional counter array, an all-sky monitor, and a high-energy array of phoswich NaI/CsI detectors with a total effective area of 2000 cm^2.

Previous studies of compact sources, based upon relatively brief observations with detectors of modest area (typically a few hundred cm^2 or in one case, HEAO-1, with large areas on a spacecraft with very limited pointing capability), have proven to be very rich. The results point directly to fruitful studies possible with XTE, especially concerning neutron stars and black holes. For neutron stars, topics XTE will address include (a) new determinations of binary orbits (including both very wide and highly compact systems) and the masses of neutron stars, (b) variations in spin rates of the accreting pulsars, (c) "quasiperiodic" oscillations in x-ray intensity, (d) phenomena associated with the intense magnetic fields of x-ray pulsars and (e) x-ray bursts from unstable thermonuclear burning of accreted material. For black holes, XTE will explore the intensity and spectral variations (such as the millisecond bursts reported in Cygnus X-1) due to accretion instabilities as matter approaches the black hole. Interest in rapid temporal variations has been greatly enhanced by the recent exciting discovery with EXOSAT of quasiperiodic oscillations on timescales of tens of milliseconds from a number of galactic bulge x-ray sources. XTE will also conduct in-depth temporal and broad-band spectral studies of x-ray novae and other transient phenomena, precession and instabilities in accretion disks, and white dwarfs. The temporal variability of bright active galactic nuclei is also amenable to study with XTE. In addition to current areas of x-ray timing research, XTE will also permit studies of qualitatively new phenomena on the shortest timescales. For the study of aperiodic phenomena, an increase in collecting area provides a fundamental advantage that cannot be obtained through longer observations.

The entire XTE observing program will be dedicated to Guest Observers through competitive proposals.

4. *U.S. Participation in the Roentgen Satellite*

The inclusion of a U.S.-provided high-resolution x-ray imaging detector in the Federal Republic of Germany's Roentgen Satellite (ROSAT) program represents an important extension of the ROSAT capability to utilize the full angular resolution of the ROSAT x-ray telescope. Participation in ROSAT will provide an ongoing capability for the U.S. astronomical community to obtain x-ray imaging data in the 12- to 15-year gap between the HEAO-2 (*Einstein*) and the AXAF missions. Both the High Resolution Imager and the German built position-sensitive proportional counter represent significant improvements in sensitivity over the comparable instruments on *Einstein*, but cover a narrower energy band. These imaging detectors can be used to carry out studies of the x-ray emission from stellar coronae, globular clusters, supernova remnants, normal galaxies, active galactic nuclei and quasars, and clusters of galaxies. Access to both of these instruments will be through a Guest Observer program.

5. *Cosmic-Ray Isotope Studies on the Combined Release and Radiation Effects Satellite*

A state-of-the-art solid state detector telescope for the elemental and isotopic identification of low energy galactic cosmic rays is to be flown as part of the NASA/Department of Defense Combined Release and Radiation Effects Satellite (CRRES) mission. This experiment extends the techniques used on

ISEE-3 to resolve all of the isotopes of the elements from hydrogen through nickel and collect statistically significant samples of all but the rarest of these nuclides. It will be able to search for isotopic effects among elements heavier than silicon that may distinguish between various models proposed to explain the isotopic anomalies observed in lighter elements.

6. *Heavy Nuclei Collector on the Long Duration Exposure Facility*

A large area of passive plastic track detectors (the Heavy Nuclei Collector — HNC) will be exposed on the second flight of the Long Duration Exposure Facility (LDEF) carrier, and later recovered for laboratory analysis of the tracks of ultraheavy cosmic-ray nuclei. This experiment will increase the total exposure for ultraheavy cosmic rays by more than an order of magnitude, and will individually resolve elements as heavy as uranium. It will be able to determine the relative contributions of r-process and s-process nucleosynthesis to galactic cosmic rays and look for connections between explosive nucleosynthesis and cosmic-ray acceleration.

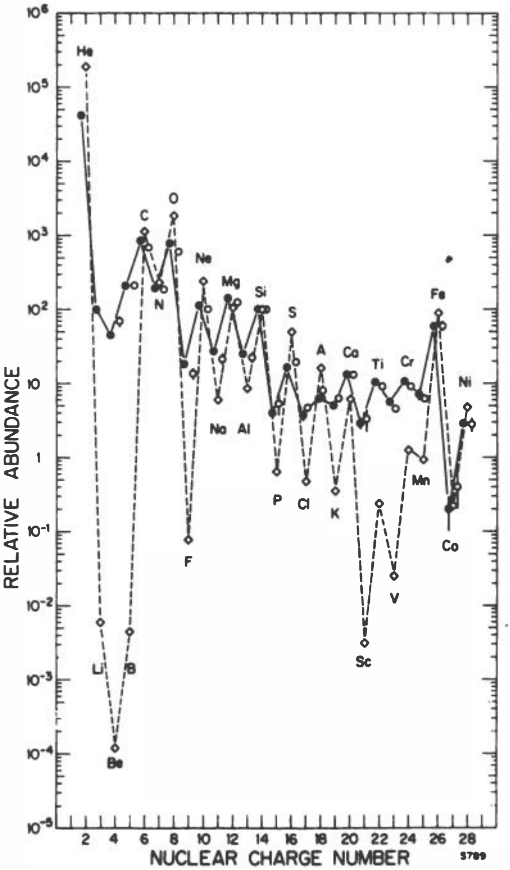
THE FUTURE PROGRAM

The dedicated astronomy missions in the current Explorer Program were selected in the 1970s. There exists a wealth of innovative new concepts for Explorer-class missions, which could be initiated when funding becomes available.

The Astronomy Survey Committee identified a number of scientific areas that appear to offer special promise for future Explorer-class missions. These include spectroscopic studies of high energy x-ray sources, determination of isotopic and elemental composition of cosmic rays, soft x-ray measurements, high energy transient phenomena, submillimeter wavelength missions, and optical and infrared interferometers. The Astronomy Survey Committee also discussed several moderate new missions which could be carried out within the Explorer

Program if international collaboration could be enlisted. These comprised, in rough order of priority, a far-ultraviolet spectrograph in space, a space VLB interferometry antenna, and a series of cosmic-ray experiments in space.

NASA has issued a Dear Colleague Letter that solicits mission concepts for new Explorers. We expect that the call for proposals to define future Explorer missions will be met with a great response, involving both those missions identified by the Astronomy Survey Committee and new concepts that have been developed since then. Many of the instruments used for remote sensing by astronomers can be profitably applied to problems in planetary science as well. The most difficult task in defining the future Explorer Program will be choosing among the many important missions that will be proposed.



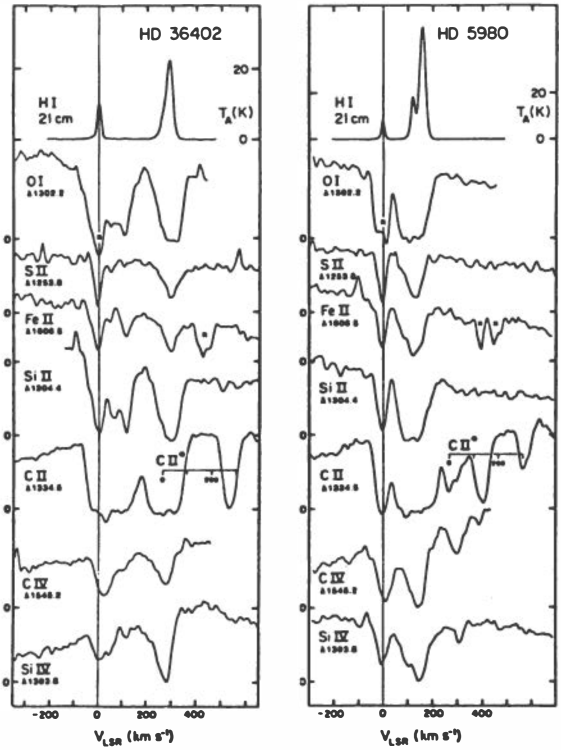
IMP Series: The relative abundances of heavy elements from helium through nickel (atomic numbers 2 through 28) in the cosmic radiation were measured on the IMP series of Explorer satellites. These values (solid circles) are compared with solar system abundances (diamonds) and with more recent cosmic-ray measurements at higher energies (open circles). The close agreement between cosmic-ray and solar system abundances of the major elements provided the first proof that cosmic-ray material is produced by normal processes of stellar nucleosynthesis. The large excesses of the rare elements Li through B and Sc through Mn have been used to measure the amount of interstellar matter encountered during the 10 million year confinement time of cosmic rays in the galaxy.

V. CONSIDERATIONS FOR AN EFFECTIVE PROGRAM

The long list of accomplishments of the Explorer Program largely resulted from the program philosophy of frequent flight opportunity, rapid response to scientific objectives, and subordination of other goals to the pursuit of first-rate scientific research. The increase of costs, which has come about for a variety of reasons, has undermined that philosophy and can diminish the scientific yield of the program. The original philosophy of the Explorer Program should be reaffirmed, and active steps need to be taken to allow the program to carry out a wide variety of scientific missions in space at a modest cost and on a relatively short time scale.

SPECIFIC COST DRIVERS

Increases in the costs of carrying out Explorer projects have escalated significantly over the past decade, resulting, in many cases, in long delays in carrying out missions. For the Explorer Program to continue to provide the maximum scientific return, the factors driving these cost increases must be understood and controlled. Significant cost drivers are present in four major areas: instrument complexity, spacecraft complexity, project engineering and management, and the interface with other NASA programs.



IUE: High resolution ultraviolet absorption line spectra of hot stars in the Large Magellanic Cloud (LMC) and in the Small Magellanic Cloud (SMC) obtained by IUE provided the first direct evidence for the existence of a hot gaseous corona or halo surrounding the Milky Way galaxy. In the two IUE spectra shown above of selected interstellar lines, absorption near 0 km/s is associated with the Milky Way (both figures), also near 270 km/s with the LMC (left figure) and near 150 km/s with the SMC (right figure). H I 21-cm emission profiles for each line of sight are shown at the top of the figures. Absorption in the Milky Way halo by such ions as Si IV, C IV and N V implies the presence of gas with temperatures in the range of 80,000 to 200,000 K. This gas has been found to extend away from the galactic plane with a scale height of about 3,000 pc.

1. *Instrument Complexity*

The complexity of the experiments carried aboard Explorer spacecraft has steadily increased over the years. While much of this increase is attributable to the maturing of the various disciplines within astrophysics and space science, some is directly attributable to the infrequency of opportunities for space flight. When flight opportunities in a field occur only once per decade, there is strong motivation to make the complement of instruments sophisticated enough to address a large fraction of the current problems in that area. The costs associated with this complexity decrease the number of initiatives that can be accommodated within the Explorer budget and further reduce the frequency of flight opportunities. A commitment to frequent flight opportunities should be made, and the scope of each Explorer project precisely defined to address a limited range of important scientific questions.

Another aspect of the interaction between delays and experiment complexity is apparent in cases where an approved Explorer is delayed so long that the proposed measurement falls behind the scientific state of the art. As delays occur, instrument designs are upgraded to avoid obsolescence, and costs rise. To alleviate this problem, it is essential that the time between instrument selection for an Explorer mission and actual flight be held to the minimum required to construct the instrument and spacecraft.

The problem of the cost growth associated with the increasing sophistication of forefront experiments in a maturing field of space science is a complex one, requiring accommodation of projects of different sizes within the overall NASA program. Certainly various flight opportunities can be identified, many of them associated with the Space Shuttle and potentially the Space Station. An issue of direct significance for this report, the distribution of Explorer Program resources between missions of significantly different sizes must be addressed. Within the criteria of scientific excellence, we recommend that a variety of experiment sizes should be accommodated while keeping the desired flight frequency of one Astronomy and Astrophysics Explorer opportunity per year.

2. *Spacecraft Cost*

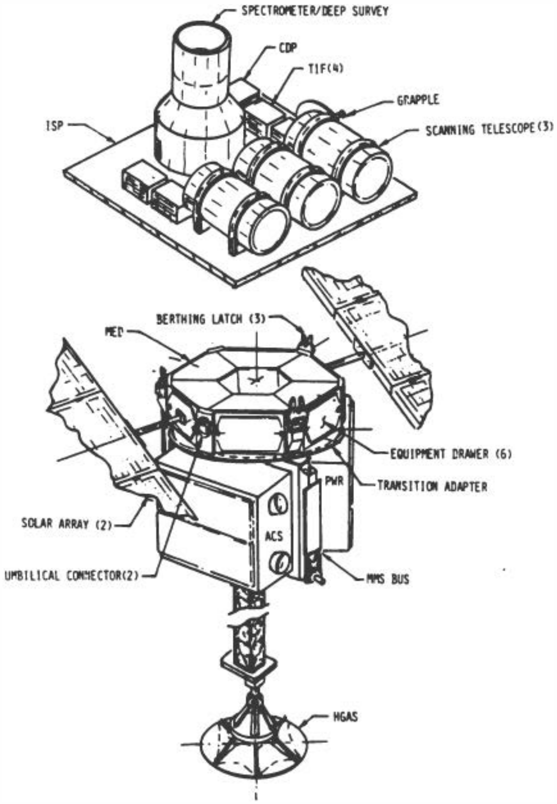
The cost of the spacecraft, as well as the integration and testing, represents the major fraction (approximately 50 percent) of many recent Explorer missions. In astronomy and astrophysics the detailed study of objects frequently requires images or spectra taken with a three-axis stabilized instrument. The pointing accuracy and stability that are necessary increase the cost of a spacecraft over a simple spinning device. In other cases, observations require cooled detectors and telescopes. Cooling increases the demand on weight and power requirements of a spacecraft which in turn leads to a more costly configuration than an uncooled system.

It appears possible to build a small dedicated platform that could meet a set of mission requirements for scientific instruments on pointed spacecraft. For instance, the Multiple Mission Spacecraft (MMS) is one such configuration. We are particularly impressed with plans to reuse the MMS as a platform for EUVE and XTE. Other concepts similar to this exist too: *Proteus* within NASA, and *Eureca* within ESA. This opportunity may offer necessary relief to the Explorer Program and allow an accelerated start for some Explorer concepts. We encourage progress in this area for those scientific missions that can be accommodated.

The use of reproducible "standard" spacecraft or platforms, *e.g.*, the MMS, derives from the same philosophy. The sounding rocket program was an outstanding example wherein a few designs accommodated a wide range of users. The existence of duplicate support systems made possible rapid turnaround of experiments. We suggest that this could also reduce costs and enhance flight opportunities.

3. *Project Engineering and Management*

For the Explorer Program to provide frequent flight opportunities for projects of limited scope, the criterion for success must be perceived as the accomplishment of a well defined, rather limited set of scientific objectives.



MMS: The MMS spacecraft now supporting the Solar Maximum Mission shown schematically with a replacement payload here depicted as the Extreme Ultraviolet Explorer. Basing in space of re-usable spacecraft such as this MMS, with the integration of new payloads to the spacecraft while in orbit, offers potential for a substantial savings in cost for future Explorer experiments consistent with the accessible orbits - such as EUVE (Extreme Ultraviolet Explorer) and XTE (X-ray Timing Explorer).

There are a number of specific engineering and management approaches that can be used to control costs. Of prime importance is detailed definition early in the project of all instrument parameters and requirements that affect the spacecraft design, and rather rigid adherence to these constraints throughout the project. In addition, adequate contingency should be established for resources such as power, weight, memory, and data rate so that the normal growth that inevitably occurs in the instrument requirements for these resources can be made without major impact on costs and schedule.

The use of previously designed spacecraft, where possible, can significantly reduce costs, but requires close cooperation between the project manager and the Principal Investigator(s) at an early stage to ensure that the experimental requirements can be accommodated. Multiple-use spacecraft designs could prove valuable to the Explorer Program. However, individual Explorer projects should not be delayed or made more costly to accommodate specific spacecraft hardware.

Explorer costs are also driven by extreme or changing experiment requirements. For example, fine pointing requirements should be carefully evaluated to avoid imposing unnecessarily stringent demands on the spacecraft design. The design and prototyping of scientific instruments to be flown should be fairly advanced at the start of an Explorer project to assure that major changes in the demands on the spacecraft will not occur as the instrument development progresses. To begin Explorer projects with well advanced instrument designs requires a significant, ongoing commitment to laboratory research into space instrumentation, and to suborbital (aircraft, balloon, sounding rocket) flights of new instruments.

The Principal Investigator of an Explorer mission ultimately carries the responsibility to achieve the scientific goals of the experiment. Management structure must allow for clear authority of the Principal Investigator. Particular care should be taken not to overburden the project with management overhead requirements that inexorably increase costs and technical complexity.

The allocation of management responsibilities among the NASA centers should establish simple, well defined lines of authority, with one center providing the prime management function, and teams required at other centers reporting directly to that management, not independently to NASA Headquarters.

4. *Interface with Other NASA Programs*

The Explorer Program has a strong record of emphasis on maximizing scientific accomplishments while subordinating other objectives to this primary goal. Requirements that result from the interfacing of the Explorer Program with other NASA projects can significantly increase Explorer costs. For example, the requirement that Explorers be launched from the Space Shuttle imposes significant safety regulations, which are costly to meet. Another example is the requirement that Explorers use the Tracking and Data Relay Satellite System (TDRSS) for communications, when in some cases this is a more costly alternative than direct communication with the NASA tracking network on the ground. Requirements such as these should be imposed only when they are more cost effective to an Explorer mission than alternative approaches such as a launch with expendable rockets or direct communication with the ground stations.

EXPERIMENTS IN COST REDUCTION

Current mechanisms for developing instruments may be unduly costly. In part, this may derive from the natural tendency to try to provide the maximum science capability on each mission in an era of few flight opportunities. The unwillingness to accept some risk of failure, related in turn, again, to scarcity of opportunity, also plays a role. We would urge NASA to study whether current management, engineering, and acquisition practices provide the highest likelihood of scientific return per dollar invested. In particular, a common, reusable spacecraft could be a cost-effective route to deriving more science from the budget for some Explorer missions.

FLEXIBLE MISSION LIFETIMES

The manyfold objectives of Explorer missions suggest that a variety of mission durations should be accommodated. In particular, the third-component (specific studies) missions can often be expected to produce rich science for periods significantly longer than the nominal 1- to 2-year Explorer lifetime. At most wavelength bands, the number and types of astronomical objects amenable to productive study are usually large, even with a given instrument. These "specific-study" Explorer instruments can have the continuing productivity for years that we expect of modest ground-based telescopes. We note the continued productivity of IUE over a period of 8 years and the high demand for observing time from HEAO-2 and EXOSAT at the end of their ~ 2-year lifetimes.

The extension of certain missions will surely raise costs. However, we know that missions designed for a 2-year lifetime (to avoid increasing the cost) will often operate substantially longer, *e.g.* 3.9 years for SAS-3. It is important, though, to avoid the inclusion of features that would prematurely limit, *a priori*, the lifetime. The growing power of small computers and modern networking could make the continued operation of an older and well understood Explorer a relatively small-scale and low-budget process. Thus the comparatively large scientific gain may well offset the modest cost increases in some cases. The vision of several concurrently active U.S. Explorers operating at different wavelength bands in conjunction with each other and with the larger "permanent" observatories, is an attractive one indeed.

SELECTION PROCEDURES

NASA has issued a Dear Colleague Letter dated March 14, 1986, entitled "Explorer Concept Study Program" to solicit concepts for future scientific missions. This Letter reflects the procedures recommended in *A Strategy for the Explorer Program for Solar and Space Physics* (National Academy Press 1984).

We endorse the philosophy and the procedures embodied in the Dear Colleague Letter. A large number of important mission concepts in astrophysics will undoubtedly result, including missions identified in the Astronomy Survey

Committee report as well as recently emerging concepts.

This new strategy for Explorer selections would enhance scientific accomplishments with the following additional considerations:

- Selection of mission concepts should take place frequently and over-selection should be stringently avoided.
- A second level of selection for Phase B studies, as described in the CSSP Report, should draw from the pool of concepts that have been studied during Phase A. This pool of concepts need not be restricted to those selected in previous preliminary rounds, if other missions with sufficient definition are available for consideration.
- The new selection procedures should maintain the present flexibility of the Explorer Program in facilitating international cooperation.

In the past, a small amount (about 5 percent) of the annual Explorer budget has been used for discretionary/target-of-opportunity efforts. We support continuation of this procedure at a similar level of expenditure. Target-of-opportunity efforts are a worthwhile component of the Explorer Program that give valuable scientific return and underscores its flexibility. We concur with the Space Science Board resolution of November 1984 that selection for participation in this discretionary component be made in a broad context. A standing committee should review scientific and programmatic considerations and evaluate other flight options. Inclusion of discretionary efforts in the program should not delay the ongoing Explorer missions.

DIVERSITY OF OPPORTUNITIES

The decrease in flight opportunities in Spacelab and Explorer Programs has led the community to develop strategies to guide NASA in the selection of new investment areas. Small, (initially) high-risk experiments, may have been "crowded from the market" of all space opportunities. Considerable improvement would follow naturally from a greater frequency of flight opportunities. Some experiments may be accommodated by opportunities other than the Explorer Program. We urge that methods for selecting experiments in the Explorer Program allow for different levels of experiments within the guidelines of scientific excellence, timeliness, and cost-effectiveness. Encouraging vigor and imagination in the long term demands a flexible approach.

INTERNATIONAL COLLABORATIONS

In astrophysics, there is a well-established tradition of international collaboration in the space program. The Explorer series has included such outstanding successes as the IRAS, a collaboration with the Dutch and the SERC of the United Kingdom, and the IUE, a collaboration with ESA and the SERC of the United Kingdom. Collaborations for future experiments include the ROSAT program of the Federal Republic of Germany. Foreign collaborators have shared in the scientific results and shouldered a substantial amount of the cost of these missions, representing 21 percent of the IUE cost and 47 percent of that of IRAS.

International collaborative programs have worked well because of the strong scientific liaison among astronomy and astrophysics researchers. Similar levels of technical abilities provide good working relationships and extremely productive scientific experiments.

Dependable funding in the Explorer line allows international commitments to be met. Collaborative scientific missions allow complementary programs to be developed. Such joint programs optimize the scarce resources of all participants.

We are concerned that a rigid and complicated selection procedure will effectively thwart the best attempts at international collaboration. To establish joint programs, simultaneous agreements among the partners must be obtained, so that costly and inefficient delays can be avoided. Selection procedures and phase A and phase B studies must not be awkwardly out of phase. The hurdles of multiple selection can make international collaboration unattractive and nearly impossible for all participants. We urge that NASA and the scientific communities work effectively to eliminate this potential problem.

Two moderate class missions recommended by the Astronomy Survey Committee of the National Academy of Sciences, appear to be strong candidates for international collaborations: A Far Ultraviolet Spectrograph in Space and a Space VLB Interferometry Antenna.

THE COST OF AN ASTRONOMY AND ASTROPHYSICS PROGRAM

The current set of obligations in the Explorer Program beginning with FY 1987 totals approximately $170M (in FY 1986 dollars). These missions include COBE, EUVE, and XTE (assuming a reusable spacecraft such as the MMS), as well as the nondedicated missions ROSAT, CRRES, HNC, and HESP*. In addition, ongoing studies and concepts to be initiated with the 1986 Dear Colleague Letter amount to about $3M per year. If the Explorer line were not augmented from the present level of $48.2M (FY 1986), and maintained only an inflationary increase, then a minimum of four years would be required to achieve these missions. Since the dedicated missions derived from initial selections in 1974-1975, this schedule implies that at least 15 years were required for completion of the programs!

These missions clearly must be completed and launched in the near term. In addition, because of the lack of dedicated Explorer opportunities for two decades, there are many new scientific concepts that must be selected and initiated. The Explorer budget line requires augmentation to continue the innovative programs and outstanding science that are hallmarks of Explorer missions.

Looking ahead to the needs of the community in

---

*HESP is a Japanese high energy solar physics mission with NASA participation.

astronomy and astrophysics and to the recommendations of the Astronomy Survey Committee, we envision a steady state of one Astronomy and Astrophysics Explorer opportunity per year. Over the next 10-year period, the mix of experiments might include (in FY 1986 dollars) the following:

3 moderate missions @ $110M average	$330M
7 small/joint missions @ $40M average	280M
current obligations	170M
studies	30M
Proposed Astronomy and Astrophysics Decade Total	$810M

This calculation implies a funding of approximately $80M per year (FY 1986) to accomplish the Astronomy and Astrophysics Explorer Program. With this budget, the direction and scope of a healthy Explorer Program can be firmly established in the next decade. During this time, we must overcome the crippling hiatus of launch opportunities, complete the backlog of missions, and rebuild a vigorous steady state in the Explorer Program. These particular circumstances may lead to more than one Explorer launch per year for astronomy and astrophysics in the immediate future.

Other disciplines, such as solar and space physics, with a long prior history of Explorer Program use, have needs that must be accommodated in the Explorer Program as well. When the programs of all communities are considered, a substantial augmentation to the Explorer budget line will be necessary.

APPENDIX: ABBREVIATIONS USED IN TEXT

ANS	Astronomical Netherlands Satellite
AXAF	Advanced X-ray Astrophysics Facility
COBE	Cosmic Background Explorer Satellite
CRRES	Combined Release and Radiation Effects Satellite
CSAA	Committee on Space Astronomy and Astrophysics
CSSP	Committee on Solar and Space Physics
ESA	European Space Agency
EURECA	European Retrieval Carrier
EUV	Extreme Ultraviolet
EUVE	Extreme Ultraviolet Explorer
EXOSAT	European X-ray Astronomy Satellite
GRO	Gamma-Ray Observatory
HEAO	High Energy Astronomical Observatory
HESP	High Energy Solar Physics Experiment
HNC	Heavy Nuclei Collector
HST	Hubble Space Telescope
IMP	Interplanetary Monitoring Platform
IRAS	Infrared Astronomical Satellite
ISEE	Interplanetary Sun-Earth Explorer
IUE	International Ultraviolet Explorer Satellite
LDEF	Long Duration Exposure Facility
LDR	Large Deployable Reflector
MMS	Multiple Mission Spacecraft
NASA	National Aeronautics and Space Administration
OSO	Orbiting Solar Observatory
RAE	Radio Astronomy Explorer Satellite
ROSAT	Roentgen Satellite
SAS	Small Astronomy Satellite
SERC	Science and Engineering Research Council (United Kingdom)
SIRTF	Space Infrared Telescope Facility
SMM	Solar Maximum Mission
TDRSS	Tracking and Data Relay Satellite System
VLB	Very Long Baseline
XTE	X-ray Timing Explorer Satellite