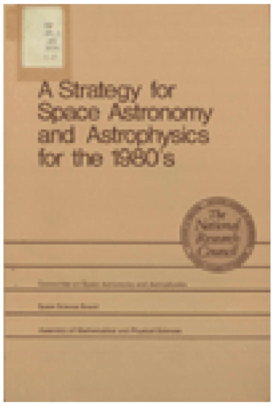

A Strategy for Space Astronomy and Astrophysics for the 1980s

Committee on Space Astronomy and Astrophysics, Space Science Board, Assembly of Mathematical and Physical Sciences, National Research Council

ISBN: 0-309-12341-0, 110 pages, 8 1/2 x 11, (1979)

A Strategy for Space Astronomy and Astrophysics for the 1980's

Committee on Space Astronomy and Astrophysics
Space Science Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

972236 PB83-174151

Strategy for Space Astronomy and Astrophysics for the 1980's

(Final rept)

National Research Council, Washington, DC. Assembly of Mathematical and Physical Sciences.

Corp. Source Codes: 019026361

1979 113p

Languages: English

NTIS Prices: PC A06/MF A01

Country of Publication: United States

Journal Announcement: GRAI8313

This report develops a scientific strategy for space astronomy and astrophysics for the 1980's. It focuses on the programs, experiments, and instruments that will be required to continue progress, on a broad front toward answering the many important and varied scientific questions that have been identified as goals to achieve.

Descriptors: *Astronomy; *Astrophysics; Planning

Identifiers: *Space missions; NTISNASNRC

Section Headings: 3B (Astronomy and Astrophysics--Astrophysics); 54GE (Astronomy and Astrophysics--General); 84GE (Space Technology--General)

NOTICE: The project that is the subject of this report 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 responsible for the report 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.

Available from

Space Science Board
2101 Constitution Avenue
Washington, D.C. 20418

Space Science Board

Committee on Space Astronomy and Astrophysics

Peter Meyer, *Chairman* (through June 1977)
Harlan J. Smith, *Chairman*
W. David Arnett
Jacques Beckers
George R. Carruthers (through May 1977)
Edward L. Chupp
Frank D. Drake (through June 1978)
Carl E. Fichtel (through June 1978)
Phyllis S. Freier
Herbert Gursky (through June 1978)
David S. Heeschen
Martin H. Israel
William L. Kraushaar
P. James Peebles
Laurence E. Peterson
David M. Rank
George H. Rieke
Wallace L. W. Sargent
Peter A. Strittmatter
Paul A. Vanden Bout
David T. Wilkinson

Richard C. Hart, *Executive Secretary*

Foreword

This is one of a series of documents prepared by committees of the Space Science Board (SSB) that develop strategies for space science for the coming decade. The Board has already issued two such reports: *Report on Space Science 1975* (Part II, Report of the Committee on Planetary and Lunar Exploration, which covers the outer planets) and *Strategy for Exploration of the Inner Planets: 1977–1987* (1978). Other reports are in preparation on solar and space physics; earth sciences; relativity and gravitational physics; comets, asteroids, and minor bodies; planetary biology and chemical evolution; and space biology and medicine.

This report develops a scientific strategy for space astronomy and astrophysics for the 1980's. It focuses on the programs, experiments, and instruments that will be required to continue progress, on a broad front, toward answering the many important and varied scientific questions that have been identified as the goals we hope to achieve.

Astronomy is a broad field of endeavor encompassing many branches of observational, experimental, and theoretical science. By necessity, this report could not exhaustively examine all subdisciplines and techniques that are at present extant in modern astronomy and astrophysics. For example, gravitational and relativistic physics, the search for extraterrestrial intelligence, and the physics of the particles and fields environment of the objects of the solar system are topics not included in this report. They will be studied, however, by other committees of the SSB, and reports will be issued when appropriate. Furthermore, the field of solar physics, while studied to some extent by the Committee on Space Astronomy and Astrophysics (CSAA), will be evaluated in great depth by the Board's Committee on Solar and Space Physics.

This strategy report has been adopted by the SSB as its policy for space astronomy and astrophysics, and it supersedes all previous reports on the subject.

The development of this strategy has been a long and difficult task. The Board owes a great debt to the members of the Committee for their diligent and untiring efforts and particularly appreciates the contributions of the two successive chairmen of the CSAA, Peter Meyer and Harlan Smith, under whose direction this report has been brought to fruition.

A. G. W. Cameron, *Chairman*
Space Science Board

Preface

For some years the Committee on Space Astronomy and Astrophysics (CSAA) of the Space Science Board has prepared for the Board reviews of scientific activities in areas of astronomy and astrophysics in space, has developed mission models and programs, and has provided recommendations on priorities in these scientific fields. Many of these recommendations have become part of the Board's statements and have been published by the National Academy of Sciences (i.e., *Opportunities and Choices for Space Science, 1974*; *Report on Space Science, 1975*).

In this report the CSAA has developed a scientific strategy for the 1980's, covering research in space astronomy and astrophysics.

In pursuing this task we had to face the fact that the variety of objects and phenomena encountered in the universe is very broad. Among others these comprise the sun and its retinue; the stars in all their stages of formation, evolution, and death; the interstellar medium; the structure and evolution of galaxies and clusters of galaxies; the most distant objects and phenomena accessible to human scrutiny—galaxies and quasars at high red shift; and the universal blackbody background. Likewise, the range of techniques used to acquire new and fundamental knowledge in astronomy and astrophysics is very wide. The radiations covered by modern astronomical observations extend over the entire electromagnetic spectrum from gamma rays to radiowaves, and include energetic particle radiations, thereby involving techniques from areas as diverse as optics, solid-state physics, low-temperature physics, nuclear physics, and elementary-particle physics. Any attempt to organize this range of scientific and technological objectives into an overall scientific strategy is therefore inherently difficult.

In addition, a plan toward the future must guard against too rigid an approach that might exclude the unexpected. One of the exciting features of astronomy and astrophysics is the fact that the rate of fundamental discoveries over the past several decades in some cases has far exceeded the rate at which a theoretical framework could be developed. The recent discovery of x-ray bursters and gamma-ray bursts is simply the latest example of this type of unexpected result.

Different subfields of astronomy and astrophysics are in quite different states of development. Some areas have recently been inundated with new and astonishing observations of phenomena that were unforeseen and unpredicted and are at this time uninterpretable. If past experience can serve as a guide, those areas that are just at the threshold of new exploration will soon lead to a further explosion of discovery.

In other more mature areas of research such as solar physics and stellar evolution, progress is achieved through a less spectacular but equally fundamental approach that involves systematic, step-by-step advances toward a deeper understanding.

Several studies, in particular solar and solar-system astronomy, offer results with a direct impact on our understanding of the earth's environment. Solar activity affects mankind through its influence on the ionosphere and on the earth's weather and climate. Deeper knowledge of the radically different atmospheres and surfaces of other planets can contribute important insights concerning the origin of life on earth and the available resources of the solar system and the consequences of their large-scale use.

In general, however, the impact of astronomical discovery is to be found in its intellectual rather than its practical contributions. These contributions, which lead to the recognition of our place in the universe and the origin and evolution of life, have been enormous and have stirred the fascination of practitioner and layman alike.

It is the view of this Committee that the most important consideration in devising a long-term strategic approach toward research in space astronomy and astrophysics is the proper balance and evolution of the scientific activities. Optimum progress over the long term can be achieved only if the sparkling and the systematic, the applicable and the purely intellectual approaches find opportunities to develop at a healthy pace.

This report does not address certain areas that are intimately related to space astronomy and that may, at some stage, use the facilities of space astronomy. These include experiments in gravitational and relativistic physics; the search for extraterrestrial intelligence; or special aspects of nuclear, atomic, and elementary-particle physics. Their omission is not meant to signify our lack of interest in these exciting areas, and we recommend that they be fully discussed by appropriate bodies.

We also note that each field of science has its generally accepted frame of reference, within which hypotheses grow, observations are planned, and progress is made. Occasionally fundamental concepts prove inadequate or even wrong and must be replaced by others; such revolutions in outlook usually lead to a surge of progress. Astronomers will regard it as a great achievement if our current widely accepted views should need revision or replacement. This is more likely to occur for the most remote concepts with the highest speculative context such as black holes, the expanding universe or its big bang origin, even the theory of general relativity itself. Meanwhile, we have used them freely and normally without further apology in this report. The proposed research is designed, to the best of our ability, to validate or disprove them along with the rest of our concepts.

The CSAA organized several panels to help assemble the background material within major disciplinary areas (i.e., solar, infrared, optical and ultraviolet, radio, x-ray, gamma-ray, cosmic-ray, and interplanetary particles). We wish to thank those outside of CSAA who contributed to these panel efforts: K. Anderson, A. Buffington, E. Chupp, W. Feldman, L. Fisk, G. Frye, G. Garmire, G. Gloeckler, K. Henize, R. Hofstadter, A. Jacobson, D. Morton, J. Ormes, R. Ramaty, B. Savage, R. Stone, D. Thompson, and G. Withbroe. Background information used in the preparation of this report included the SSB priority studies of 1974 and 1975 and the reports by CSAA contained therein, the SSB summer studies on the scientific uses of the Space Shuttle (1973), on Infrared Astronomy (1975), and on Solar Physics (1975), the report by the *ad hoc* Committee on High Energy Astrophysics (1974), and the interim report of the astronomy Spacelab payloads studies (NASA-GSFC, 1975). In addition, briefings by the personnel of the NASA Office of Space Science provided important inputs to the Committee's work.

Not many will have occasion to read the entire report. Accordingly we have organized it into four distinctly different parts:

Chapter 1 is a brief introduction calling attention of nonastronomers to a few aspects of the fantastic range and majesty of the astronomical and astrophysical phenomena now opening up to investigation through space techniques.

Chapter 2, with only outline justification, summarizes our strategic approach and specific recommendations for ready reference by interested readers. The remainder of the report provides, from two different points of view, the more detailed scientific and technical rationale that led to the recommendations.

Thus, in Chapter 3 we have organized the scientific topics of this report not according to astronomical disciplines but rather according to the objects under study. By describing the scientific objectives in some detail, this approach displays most clearly how our understanding of astronomical phenomena is gained through the synthesis of results from a wide range of techniques.

Nevertheless, the efficient planning of experiments and gathering and interpretation of data must nearly always be done by discipline-oriented astronomers through specific missions. Consequently, Chapter 4 develops, field by field, the rationale for the programs that are needed.

This report is meant to serve as a guide toward implementing a scientific strategy in space astronomy and astrophysics for the next decade. We have chosen to present our principal summary conclusions in the form of a recommended general ordering of development for various activities in the different branches of space astronomy and astrophysics. While thus not developing a detailed mission model, the Committee wishes to stress that it has, at all times, tried to consider its recommendations within the constraints of our understanding of the "real world." The specific proposals made here are far from being an exhaustive or maximal list of opportunities. Rather, they represent a careful winnowing from a much larger set of potential candidates, to bring out only those that have the highest scientific promise and urgency.

Astronomy, including astrophysics, has always been one of the most influential sciences, instrumental in the discoveries of the basic laws of nature. It has been among the most challenging and exciting of all human activities of the past two decades, in considerable part because of the strong support from and the great success of the NASA programs. Many important new results lie just ahead.

Contents

1
Introduction

What is the nature of the universe? This question has been asked since the beginning of rational thought. The remarkable central fact of astronomy is that we can find objective answers. In ancient times people had already learned how to predict eclipses. Three hundred years ago Newton established that a simple universal law of gravitation could account for falling objects on the earth, the motions of moons around planets, and the motions of planets around the sun. One hundred years ago, optical spectroscopy revealed that stars are composed of ordinary matter, thereby initiating work on stellar classification and evolution theory. Fifty years ago Hubble, Friedmann, and Lemaître may have discovered the dynamics of the universe itself—expansion from a big bang. These are a few milestones among many in the growth of understanding. Each depended on what came before; each stimulated new search and discovery. We see no end to this great enterprise, for whenever the universe is explored in greater detail or in new ways, old errors are corrected and new things are revealed. As simple riddles are answered, deeper ones appear.

Today observations are expanding as never before. It is only a few decades since our view was limited to the narrow band of visible light. Now a remarkable variety of information carriers can be read for the messages they bring from the universe. These include radio waves, x rays, gamma rays, and cosmic rays—observed from the earth and from deep space. True to form, each of these has uncovered a wealth of new phenomena and questions. A full text in astronomy would be needed to relate them all. In this Introduction let us remark on several.

We have learned that the space between the stars is occupied by more than merely simple gas and dust. Vast regions exist in which complex chemical compounds are manufactured in great abundance. These include some of the same organic molecules that on earth play a role in living organisms. How did this chain of chemical reactions arise, how does it work, and to what end? The answers will require ultraviolet, infrared, and radio telescopes lifted above the obscuring molecules of the earth's atmosphere.

Imbedded in the interstellar matter is evidence of the birth of stars and planets. Initially, cold dark cocoons of gas and dust are squeezed ever smaller by their own self-gravity, heating as they shrink, until nuclear fusion is ignited in their cores. These regions are optically opaque, but far-infrared radiation brings information concerning this creation of new worlds–information that we can read only by launching large refrigerated infrared telescopes into the clarity of space.

The stars themselves show new phenomena when seen from space. Their outermost atmospheres, or coronas, have been found to glow at x-ray wavelengths, revealing the presence and nature of flare phenomena as on the sun and of energetic particles streaming out to interstellar space. X-ray observations of such atmospheres can help to show how our own sun works, and perhaps how such phenomena may play a role in the weather of the earth. Similarly, the persistent failure to detect the expected flux of neutrinos from the sun's interior suggests that even in supposedly well-understood situations we may still have much to learn.

The excessive brilliance of the more massive stars soon exhausts their reserves of nuclear energy. They collapse by their own self-gravitation and are destroyed by the catastrophe of a supernova explosion, hurling into space most of the ashes of their nuclear fuels while the innermost core contracts evermore tightly. Objects are created with densities so great that matter subsequently falling onto them is heated to millions of degrees, giving rise to energetic x-ray and gamma-ray emission. Some of the objects are neutron stars, in which each cubic centimeter weighs a billion tons. Some give off x rays in an orderly series of bursts; others emit large bursts of gamma rays. Some may be black holes. Probably there are types of objects or phenomena that we have not yet contemplated.

Behind these neighbors everywhere in the sky is the faint gleam of x rays, perhaps the glow of a turbulent superhot gas between the galaxies. Also speeding in the space between the stars and galaxies are cosmic rays, the products of the most energetic reactions and acceleration processes in our galaxy. They may be markers and relics of places where elements are born; they reveal their presence by the emission of gamma rays of high energy. Observations from space are needed to study such kinds of radiation.

The sun produces more than a thousand trillion times the total energy used by the entire human race. A supernova exceeds this by tens of billions of times. Yet the brief violence of a supernova explosion may be still further exceeded by hundreds or even thousands of times in continuing activity at the centers of some galaxies and quasars. What produces such energy? By what mechanisms do these objects spew out energetic particles in jets or radiating clouds filling millions of cubic light years of space? Here, as with supernovae, we may be facing the limits of our best current understanding, according to which the most intense gravitational fields may curl space-time into singular knots—black holes—where our knowledge of physics breaks down. To learn what is happening even on the edges of such objects we need to examine the radiation from them in detail with infrared, optical, ultraviolet, x-ray, and gamma-ray telescopes of great sensitivity. We must image them distinctly with radio telescopes in space having resolution so high as to require antenna spacings greater than the diameter of the earth.

In every area of astronomy, theory, unless tested by observation, remains speculation. Conversely, raw observations, by themselves, are almost useless. They take on meaning only in the context of a theoretical interpretive framework. Modern physics and astrophysics provide such a framework. Much of this structure is relatively secure, but part is rather provisional, with some of the most exciting frontiers such as the possibility and properties of black holes being quite tentative. Our present comprehension of cosmic objects and phenomena has developed over the centuries through intimate interaction of theory and observation. This will continue to be the case as we pursue ever deeper problems.

The results of the first forays into space are now in. We know the excitement of the discoveries that have been produced and are ready to continue with this great endeavor—the exploration of the universe.

2
Strategy and Recommendations

Chapter 1 has touched on a few of the fundamental questions that we are able to pose and to begin to answer about the physical universe in which we find ourselves. These studies are now possible thanks in particular to the strong backing provided by the American people through Congress, the Executive Branch, and the National Aeronautics and Space Administration. We speak for all of our colleagues in expressing deepest appreciation for this splendid support, which has launched our discipline into space and provided it with tools beyond the dreams of astronomers only a generation ago.

The first explorations have now been made. We see clearly where the research needs to go, and trust that the essential resources will continue to become available. If past experience is any guide, the investment will be returned manyfold to future generations through applications now unforeseen. To our generation, the return is mainly in terms of knowledge, insight, and intellectual satisfaction. We suggest that this remains an investment worthy of continued strong support. In that spirit we present in this chapter the essential space-astronomy program for a balanced effective exploration of the universe over the next decade.

PHILOSOPHY OF STRATEGY RECOMMENDATIONS

Each field of science develops techniques appropriate to its problems. Astronomy, by virtue of the vastness of the universe and our inability to perform experiments on it, of necessity has been the most purely observational science. It proceeds by looking at the richest feasible selection of objects across the widest possible range of wavelengths, first to discover what exists, then, by classifying and comparing, to begin to understand. Insight begins to come with the creation of theoretical models based on and interactive with the best available physics. Astronomy has often stretched physics to its limits and now promises to test it in realms beyond the hope of laboratory work. The space-astronomy programs developed in the remainder of this document stress these essential aspects of the field:

- The discovery of novel entities, frequently as a result of opening up new ranges of observation;
- The finding of many examples to permit classification and study of interrelations;
- The detailed analysis of selected members of the group by each available technique;
- The development of theoretical models; and
- The carefully conceived observational tests of the evolving theoretical framework, even of the physical laws themselves.

To carry out this program requires all the resources of astronomy, with ground-based optical and radio observatories continuing to have a major role. As just one example from many, x-ray binary stars, first discovered by satellite observations, were soon also detected by optical and radio telescopes, and a preliminary theoretical understanding of their nature was rapidly worked out. Even the more familiar objects often need the widest possible range of wavelength of observation for us to really understand their properties. Ideally, if suitably sensitive instruments were continuously available for all spectral regions, our insight into the universe would increase dramatically. Although astronomers hope eventually to reach such a goal, at present it is neither feasible nor necessary to do so. What is needed is an orderly progression of inquiry into the diverse objects and effects, near and far, that populate the cosmos. Some of the observations are exceedingly difficult, requiring large and costly missions into space, while others are relatively simple and inexpensive. Some can be carried out with existing technology, while others require extensive development.

The recommended detailed strategy is based on many considerations. Foremost were the scientific questions—the quantity and quality of fundamental results to be expected and their relevance to other fields of astronomy and science or to important applications. But the science can only develop in a context of real-world constraints. We have thus tried to take account of spacecraft development, propulsion capability, and new instrumentation, also of scheduling within the on-going space program, the continuity of effort within the various scientific disciplines, and, of course, budget limitations.

The resulting strategy is summarized in the remainder of this chapter primarily as a sequence for the proposed astronomical missions during the 1980's, as well as some that should be in preparation for the 1990's.

SUMMARY AND RATIONALE OF RECOMMENDED PROGRAM

Introduction

The purposes and goals of the program are outlined briefly in this chapter along with our specific recommendations. The various missions are described in more scientific detail in Chapter 3 and by discipline in Chapter 4. Some are well-known and well-studied concepts; others are relatively new ideas. Both types have been included in order to specify an appropriate sequence of effort that we believe will lead to the most rapid deepening of our understanding of the universe. As noted above, use of different wavelengths brings new physical phenomena into view—we literally see the world in new and different lights. Several kinds of observatories are required to make this possible. Gamma-ray, x-ray, UV-optical, infrared, millimeter, radio, cosmic-ray missions—none of these can really substitute for any other; each allows us to contact a different and essential aspect of the universe.

Recognizing the essential unity of astronomy, in this document we propose a limited yet balanced approach, which, by the end of the 1980's, will effectively open our eyes to most of the major information carriers from outer space, each bearing its unique kind of message.

Classes of Missions

Although the distinctions are not always simple or clearcut, astronomical space missions generally fall into classes that we refer to as moderate and major.

Moderate missions tend to be modest in cost and limited in goals, concentrating on brighter objects or specific observations over short flights or lifetimes, and with results obtained by a small group or occasionally even a single principal investigator. Such missions are extremely valuable for a variety of reasons, including pioneering new fields, testing equipment, performing critical observations, and supplementing the larger systems. They must not be neglected in any rational strategy, and they are discussed in the appropriate places below.

Nevertheless, in this report we have stressed the *major missions*, typically costing more then $100 million, because their unique qualities are essential to advance the frontiers of knowledge. The task of each is so extensive that in some cases the mission is called an "observatory." The term implies nothing specific about lifetime, although two of the missions (Space Telescope and X-Ray Telescope) should be true observatories with useful lives perhaps reaching several decades. In general, with the wealth of different objects to be studied and the promise of major discoveries, the longer a system continues to operate the more cost-effective and scientifically productive it will be. However, most of the major missions do not necessarily involve long-term operating commitments.

In these connections we call particular attention to the great capability for astronomy represented by the Space Transportation System (Space Shuttle), whose development is nearing completion, with first flights scheduled for late 1979. With its large payload capacity, the Shuttle will be invaluable for many future applications. Spacelab will remain in orbit for one to four weeks, and it will provide common mounting and housekeeping facilities for a variety of instruments for which these relatively short mission durations are adequate. The Shuttle will also serve as the vehicle for carrying "free-flying" satellites into orbit. These free-fliers will be placed in orbit by the Shuttle and remain there for extended missions (one to several years). The Shuttle will further offer the capability of periodic visits to service these free-fliers, as well as the opportunity of recovering them and returning them to earth. A common space platform may provide advantageous mounting and servicing possibilities for some of these satellites. Explorer-class missions have traditionally constituted a subset of the free-fliers costing less than about $30 million; the concept is useful, but in view of inflation and growing instrumental sophistication the ceiling should now be appreciably increased.

Instrumentation on either the Spacelab or the free-fliers is in some cases a "facility," i.e., a large, relatively expensive piece of equipment that can be adapted to a variety of observations, such as a large telescope that can perform various studies depending on where it is pointed and what detector is in the focal plane. In other cases, principal-investigator- (PI) class instruments are appropriate; these are relatively less expensive than typical moderate missions and are normally more special-purpose devices, for which a single investigator or a small group of investigators is responsible for instrument development and the full scientific investigation.

Summary of Strategy

The strategy at which we have arrived focuses on five major missions for the coming decade, also on a number of essential tasks to be carried out with Explorer-class and Shuttleborne instruments, as well as with rockets, balloons, and aircraft, on support for theoretical studies to help guide observations and to make possible their interpretations, on proper attention to the analysis and interpretation of data, and on the need for planning and development for the next generation of instruments.

The major projects detailed below (Space Telescope, Solar Polar, Gamma-Ray Observatory, X-Ray Telescope, and Cosmic-Ray Observatory) are for space astrophysics the main instruments of attack. They should be built and launched well before the end of the coming decade, with others under active study and development to follow at the appropriate times. These projects will mount a powerful assault on many urgent astronomical problems. But, like any major arms of attack, they cannot function without auxiliaries. The programs to be based on Spacelab and Explorer-class flights (see below), and the supporting developments especially of theory and data handling, make up these essential auxiliaries.

The five major projects that undergird the recommended program for the 1980's represent the highest-quality scientific instruments. They will achieve the goal of a broad investigation of the scientific problems discussed in Chapter 3. These projects are listed in priority order below for the following reasons:

1. Those missions of primary scientific content that have been fully studied and that fit immediately into the ongoing space program deserve the highest priority:

- The *Space Telescope*, a fiscal year 1978 new start, is the most important new project in astronomy because its high resolving power, faint limiting magnitude, broad wavelength coverage, and freedom from atmosphere distortions will provide optical and ultraviolet astronomy with at least an order-of-magnitude increase in instrumental capability.
- The *Solar Polar* mission, approved for a new start in fiscal year 1979, will explore for the first time a whole new regime of the solar system—the environment out of the ecliptic plane and over the poles of the sun.

2. The three following projects are also of the highest scientific merit and should be initiated as soon as resources and technical state of the art allow:

- The *Gamma-Ray Observatory* (GRO) will be a major advance into a spectral region that is characteristic of the most energetic interactions and violent events in the cosmos, a spectral region that we have just barely begun to probe. We know from experience that many of the most remarkable discoveries in astronomy have come from looking into each new realm of observation as it is opened by the advance of technology. The GRO is a key element in our strategy for a balanced advance of the science.
- The *X-Ray Telescope*, by virtue of larger and higher-quality optics, better detectors, improved pointing flexibility, and much greater lifetime, will represent one to two orders of magnitude gain in scientific performance over HEAO-2. The field is ripe, its scientific promise is immense, and the technology is nearly ready.

• The *Cosmic-Ray Observatory*, representing the culmination of many decades of research, will become timely as soon as the results of current and pending cosmic-ray flights permit final design of the optimum complement of instruments.

Continuation of effective astronomy through and beyond the next decade will depend on long-term development of appropriate instruments and spacecraft facilities. Detailed plans in many areas need to be worked out over the next few years; future reviews will consider their relative urgency and priority. Meanwhile, we suggest a highly tentative relative sequence for the beginning of substantial studies of further major mission concepts: solar probe (also involving other science including relativity, and particles and fields); x-ray observatory (probably stressing larger aperture); radio-astronomy free-flier for very-long-baseline interferometry; gamma-ray observatory follow-on; x-ray observatory (probably stressing spectroscopy and polarimetry); optical–IR interferometer; cosmic-ray observatory follow-on; large submillimeter free-flier; very large radio-astronomy antenna; large optical–IR flux collector.

Along with major missions, there are a number of essential tasks to be carried out with Explorer-class and Spacelab instruments. The development of *a Spacelab diffraction-limited 1.2-m solar telescope* will be a primary tool in studies of solar activity. A *meter-class cryogenically cooled IR telescope* for the Shuttle appears to be the next fundamental step in infrared astronomy after the survey satellite (IRAS). In addition, for stellar and extragalactic astronomy, a wide variety of instruments can be tested and utilized for important new observations including deep moderate-field (0.5°) high-resolution imagery using a *Shuttle-based meter-class optical telescope* available for up to several flights per year.

Space projects of the Explorer class are ideal to back up the major missions for work in x-ray, extreme-ultraviolet, and cosmic-ray observations. An *Explorer-class x-ray timing instrument* is entirely adequate for the important long-term study of variability of bright x-ray sources. Monitoring of the *cosmic radiation background* falls into the same category.

Although not yet fully evaluated by this Committee, a number of additional moderate or PI-class missions already stand out as probably worthy of development and flight. These include for Spacelab a deep ultraviolet survey telescope, a solar grazing-incidence x-ray telescope, a prototype very-long-baseline radio interferometer, a submillimeter telescope, and a solar hard x-ray imaging telescope. For Explorers, it may prove cost-effective as well as scientifically important to add missions for x-ray spectroscopy and x-ray polarimetry to follow x-ray timing. A solar stereoscopic mission may also have interesting possibilities.

This strategy also needs to be backed up with a program of rockets, balloons, and aircraft for the development and testing of new instruments as well as for making specific observations at relatively low cost.

Finally, the most effective and efficient use of these magnificent space instruments requires adequate provision for supporting ground-based observations and laboratory data, for data handling and analysis, and for the theoretical studies that so often point the way to the most fruitful observations as well as give meaning to them all.

SPECIFIC MISSION GOALS AND RECOMMENDATIONS–MAJOR MISSIONS

Space Telescope

A substantial fraction of all the matter in the universe lies in the general temperature range of 10^3 to 10^5 K, emitting light from the intermediate ultraviolet to the near infrared. Because of the abundance of atomic and molecular spectral features in this region, the information content of the light is immense. This is the spectral domain utilized by classical telescopes. However, the earth's atmosphere blocks ultraviolet radiation below 3000Å and absorbs heavily in many broad infrared spectral regions beyond 7000Å, while atmospheric disturbances limit the effective angular resolution of ground-based telescopes to about a second of arc. Although two small telescopes (Copernicus and the International Ultraviolet Explorer) are operating in space and have yielded much important new information about the ultraviolet region, their spectral range and spatial resolution are limited, and their light-gathering power is far below that of their ground-based counterparts. As detailed in the following chapters, many of the most important problems in modern astronomy require large, high-resolution (where possible, diffraction-limited) optical systems outside the earth's atmosphere. These problems include, among a myriad of others, the physical and chemical properties of the interstellar medium, the nature of binary x-ray sources and accretion disks, the nature and evolution of quasars including their relation to the violent quasarlike activity in the nucleus of some relatively nearby galaxies, the existence and properties of black holes, the cosmological distance scale, and the geometrical character and evolutionary history of the universe.

Astronomers everywhere have hailed the authorization by Congress in 1977 of the first major instrument of this type, the 2.4-m Space Telescope (ST). *We recommend that priority be given to the successful completion, deployment, long-term operation, and refurbishment of the ST, including optimum instrumentation and detectors with appropriate changes of this equipment at intervals of several years, as well as to the strong programs of ground-based observations, theoretical analysis, and data support necessary for its most effective use.*

Solar Polar Mission

Studies of the sun and of the universe have so far been done only with instruments located in the narrow ecliptic plane. For a number of astrophysical objectives, this restriction has proved to be a major handicap. Among these, a definitive study of the solar wind including its angular velocity will only be possible by sampling the flow and by measuring the magnetic fields at all heliographic latitudes rather than just near the ecliptic, which happens to coincide closely with the solar equator. Observations over the solar poles are likely to result in an almost uninhibited view of galactic cosmic rays, which are unable to penetrate the solar system down to the ecliptic because of the complex magnetic-field structure at low heliographic latitudes. The Solar Polar Mission is truly an interdisciplinary venture. Apart from solar physics, space physics, and galactic cosmic-ray studies, it provides an ideal opportunity for the precise location of gamma-ray burst sources by means of triangulation, for the study of the propagation of radio bursts and their exciters in the circumsolar region, and perhaps for the study of interstellar dust.

This is a well-studied program, ready for action. A new start now will assure a solar polar passage at the next solar minimum when solar conditions are optimum for cosmic-ray and solar-wind studies.

We therefore support the Solar Polar Mission as a new start in the NASA fiscal year 1979 budget. We also support the concept of suitably instrumented companion spacecraft to provide similar and simultaneous information on the solar wind, on cosmic-ray fluxes in the ecliptic plane, and on other objects of study on the solar polar spacecraft, provided these can be placed on already approved missions; in the event that new missions would be required primarily for this purpose, we believe that further study of this concept would be necessary.

Gamma-Ray Observatory

Gamma-ray astronomy permits direct study of many of the largest transfers of energy occurring in astrophysical processes, including rapid expansion processes, explosions, high-energy particle acceleration, gravitational accretion to superdense objects, fundamental processes of the building of the elements and even perhaps their total annihilation should antimatter be anywhere abundant. Because their interaction cross section is low, gamma rays have a high penetrating power and can reach the earth from parts of the universe, such as the center of our galaxy or dense regions near the center of the active galaxies, which cannot be viewed in the optical or low-energy x-ray region. However, the earth's atmosphere prevents gamma rays from reaching the earth's surface in primary form and raises the level of background gamma radiation because of cosmic-ray interactions. Hence, it is necessary to carry gamma-ray instruments above the atmosphere.

Gamma-ray astronomy is undergoing an orderly progression from the initial discovery phase with instruments riding small U.S. and European satellites (SAS-2 and COS-B) through the exploratory phase on balloons and on the U.S. High Energy Astrophysical Observatories (HEAO-1 and -C). A major new start with instruments of large sensitivity is now needed for the solution of fundamental problems such as (a) understanding the dynamic and evolutionary processes associated with neutron stars and black holes, as well as with gamma-ray-emitting objects whose nature is still a mystery; (b) search for direct evidence of nucleosynthesis, the elemental building process in nature; (c) exploration of our galaxy in the gamma-ray range with particular regard to regions difficult to observe at other wavelengths; (d) origin and dynamic pressure effects of the cosmic rays; (e) study of high-energy particles and energetic processes in other galaxies, especially radio and Seyfert galaxies, and in quasars; and (f) cosmological clues including direct evidence bearing on the matter–antimatter symmetric big-bang theory and on primordial black-hole emission. Such scientific goals require a set of large individual experiments that may advantageously be combined into a substantial Shuttle-launched free-flying spacecraft. These instruments must have the capability to survey high-energy (>30 Mev) gamma-ray sources and diffuse emission with energy resolutions around 15 percent and point-source sensitivity of 10^{-7} photon cm^{-2} sec^{-1} or better, also with about 8-arc-min angular resolution on strong sources. For low-energy gamma rays the target is around 25 percent resolution with sensitivity of 10^{-5} photon cm^{-2} sec^{-1}. Nuclear gamma lines need to be identified with energy resolution <0.4 percent and sensitivity of the order of 10^{-5} photon cm^{-2} sec^{-1} in order to analyze the interstellar medium and supernova shells. Gamma-ray bursts require instruments able to study spectral and temporal behavior, as well as to locate the sources within 0.1 deg. The technology now exists to build appropriate instruments, and development has progressed to the point where construction of flight units can occur.

We recommend a free-flying spacecraft with a large payload capacity dedicated to gamma-ray experiments as the next important mission to initiate. The state of technology and the importance of the science indicate that an early start on a gamma-ray observatory is desirable. Even a 1980 new start implies a five-year gap in gamma-ray observations before the Gamma-Ray Observatory can begin operation.

X-Ray Telescope Facility

Small-aperture x-ray rockets and spacecraft have revealed an unexpected universe of energetic phenomena. On the stellar scale these include corona and flare activity of ordinary stars, transfer of matter in close binaries, accretion onto the surfaces or onto disks surrounding degenerate stars, acceleration of matter by rotating neutron stars, and perhaps even the descent of matter into black holes. On the galactic scale it is becoming clear that much of the important action—especially in quasars, galactic nuclei, and the intergalactic regions—involves temperatures in the range of 10^6 to 10^9 K, where x rays carry most of the information.

The first High Energy Astrophysical Observatory, HEAO-1, has carried out the important task of mapping the bright x-ray sources over the sky. HEAO-2 is now providing 3-arc sec resolution over a 30-arc min field and has increased available sensitivity by several hundredfold without attendant problems in source confusion. This allows the study of bright stellar x-ray sources such as Cen X-3 and Cyg X-1 in nearby galaxies and the detection of extragalactic x-ray sources at 10 to 20 times the distance of currently detected objects. Also, spectral studies are greatly facilitated by the use of its high-efficiency spectrometers. HEAO-2 is having major impact on a wide range of astronomical problems, but it is still an exploratory craft with limited range of instrumentation, and at best it is strictly a time-limited (several-year) mission, ending as the 1980's begin. The discipline has matured to the point where a semipermanent (several-decade) national observatory facility of this kind, open to all astronomers and with instrument-changing possibilities, is necessary. More than an order-of-magnitude improvement in sensitivity over HEAO-2 is required to allow high-resolution spectroscopy and in-depth studies of specific objectives such as clusters of galaxies and active galaxies. This can be achieved by a combination of greater telescope size, better optical surfaces, improved focal-plane instrumental sensitivity, and longer mission duration compared with HEAO-2. The advent of the Shuttle transportation system makes this feasible. Such a mission will be one of the most important elements in the entire astronomy program to the end of this century. The inevitable long gap between the end of the HEAO-2 mission and the launch of an x-ray observatory makes an early start particularly urgent.

We recommend that a long-term free-flying maintainable and retrievable x-ray observatory based on a telescope of the 1- to 2-m class be initiated at the earliest opportunity consistent with the overall space-astronomy strategy.

Cosmic-Ray Observatory

Cosmic rays offer a unique sample of material from outside the solar system, bringing direct evidence of nucleosynthesis and particle acceleration, likely associated with supernovae. Observations to date indicate that cosmic rays are enriched in products of explosive nucleosynthesis and also imply an enrichment owing to preferential acceleration of elements with lower first-ionization potential. To unravel these kinds of enrichment and to probe directly the explosive nucleosynthesis processes, accurate measurements are required of isotopic composition of elements from hydrogen through nickel and of individual element abundances through plutonium. Measurements of elemental abundances to substantially higher energies than the 100 GeV/amu achieved so far are needed to test and constrain acceleration models.

Cosmic rays are an important constituent of the interstellar medium. Measurements of their confinement time traversed in the galaxy bear on questions of galactic structure and on the distribution of cosmic-ray sources. Recent observations indicate a propagation lifetime at low energies of the order of 20 million years in a region of low average gas density, and shorter propagation at higher energies. Improvement in understanding the galactic dynamics of cosmic rays requires abundance measurements over a wide energy range of several unstable isotopes and of actinide elements (which have only unstable isotopes) and extension to substantially higher electron, positron, and proton energy.

These cosmic-ray observations can be performed with a set of PI-class instruments, which are well within the current state of the art. Though each serves a single investigator group rather than being a general-user facility, the instruments are large, so the set would fill a Shuttle payload. They all benefit from coarse pointing away from earth (simpler than the fine stellar pointing required by other astronomical instruments). They all require exposure of the order of two years to achieve definitive results.

The Cosmic Ray Observatory should be initiated as soon as results are available from HEAO-C, International Sun-Earth Explorer (ISEE)-C, Spacelab-2, and several balloonborne experiments. The precise complement of detectors and their specifications must be reviewed at that time.

We recommend that a free-flying spacecraft be launched in the mid-1980's carrying a dedicated cosmic-ray payload of four or five independent principal-investigator-class cosmic-ray instruments.

Planning Activities for Other Major Missions

A number of other major missions, although important elements of the next decade's strategy, have not yet been studied carefully enough to warrant secure assignment of relative priorities in our specific recommendations. We suggest a reasonable tentative order and pace of development. In each case a sufficient study phase will be needed before a new start becomes appropriate. *We recommend that studies of the following mission concepts be continued or undertaken in a fashion that will lead to an early and orderly progression of new starts in the astronomical and astrophysical sciences.* Briefly described below are some of the principal scientific and instrumental objectives for each of these missions.

FOLLOW-ON X-RAY OBSERVATORIES

Certain important objectives of x-ray astronomy cannot be met by the recommended national facility X-Ray Telescope, in particular because the requirement of high-resolution, grazing-incidence focusing optics prevents the attainment of large collecting aperture and also imposes a high-energy cutoff. Scientific objectives to be optimized with later observatory-type missions include moderate resolutions (about 1 arc min), high-sensitivity surveys, timing, high-energy (>7 keV) observations, spectroscopy, polarimetry, and all-sky monitoring. Where possible, such missions should make use of grazing-incidence x-ray optics, perhaps in modular form, that emphasize very large effective collecting area rather than imaging quality. Several experiments may be grouped together to form a single mission in the style of HEAO-1. As a general guideline it must be demonstrable that order-of-magnitude improvements in performance can be achieved with observatory-class missions rather than by incorporation of the instrument into Shuttle, Explorer, or Telescope Facility missions.

NASA needs to maintain active x-ray working groups in order to define prospective missions as the scientific priorities become better established, based on HEAO-1 and HEAO-2 results.

GAMMA-RAY OBSERVATORY II

Gamma-ray results available so far have shown considerable spatial structure in the distribution of the intensity from the galactic plane. The Gamma-Ray Observatory will separate the diffuse galactic radiation from the point sources, study the cosmic-ray distribution and pressure effects, search for the origin of cosmic rays, look for evidence of nucleosynthesis, and detect extragalactic objects. When the general nature of the gamma-ray sky is in hand, it will then be necessary to concentrate on the detailed features of specific compact sources, clouds, galactic arms, nearby galaxies, and probably QSO's. To accomplish this study, a very specialized high-energy telescope as well as a high-resolution nuclear gamma-ray spectrometer will be needed. Initial study of these instruments should begin as the results from the Gamma-Ray Observatory are becoming clear; they could be flown on a large observatory at an appropriate time around the end of the next decade.

ADVANCED FACILITIES FOR RADIO ASTRONOMY

Although only a handful of radio-astronomy experiments have been flown in space, we believe that the potential of space for radio astronomy is so great that it is essential now to begin detailed studies of ways to exploit this opportunity.

Important ideas include a free-flying very-long-baseline interferometer, a large free-flying submillimeter telescope, and a very large (several kilometers) radio antenna. Although these instruments are discussed in more detail in Chapter 4, they are by no means well defined. We recommend serious study of these concepts through the mid-1980's, leading toward possible missions in the following decade.

ADVANCED FACILITIES FOR OPTICAL ASTRONOMY

The Space Telescope (ST) will provide a tremendous advance in our ability to gather high-quality optical data, particularly in terms of sensitivity and spatial resolution. However, some important astronomical problems already need orders-of-magnitude improvement in angular resolution and aperture over the ST. To recall just a simple example, many fundamental aspects of stellar evolution still elude us because of lack of basic information on the masses and luminosities of stars—information that can be obtained by studying nearby stellar systems with high angular resolution. Because of the long period required to develop this new technology, it is perhaps appropriate to raise the question of what shall eventually come after ST.

Technical means exist to address this problem. It should be possible in space to use optical telescope arrays, much in the style of the ground-based radio astronomy Very Large Array, for which each unit is of modest size and the beams are combined coherently. A start in this direction could be an interferometer comprising two telescopes each of 1-m diameter, separated by 10 m. Such a configuration would possess angular resolution in one dimension of 0.01 arc sec. Because of its high sensitivity, it could address important questions in astronomy. Such an instrument is suitable for Spacelab. The knowledge gained from such an instrument, coupled with NASA's ongoing development of large structures in space, could be used to plan extensive arrays of substantially larger apertures over baselines of up to hundreds of meters.

The possibility of placing in orbit very-large-area flux collectors with imaging capability approximately the same as ST, namely 0.1 arc sec, also requires examination. Experience with ground-based telescopes suggests that an instrument of aperture 10–25 m will be required to exploit this angular resolution fully. This is due to both the low surface brightness of many extended sources and the very faint levels at which point sources can be detected above the sky background (~27–29 magnitude) at 0.1-arc sec resolution. The information rate from such sources is extremely low. For example the ST will be able to detect only one or two photons per minute from a 29th-magnitude object. The very large flux collector would exceed the size of the Shuttle and would undoubtedly have to be assembled in space. Hence, it would require a totally new approach to design and deployment if the cost is to be acceptable. Recent technological advances in active optics suggest that the latter condition can be fulfilled. Studies of appropriate techniques for achieving this goal should be initiated soon, in anticipation of missions in the 1990's.

COSMIC-RAY OBSERVATORY II

Several kinds of cosmic-ray measurements require further developments of detector technology and/or the ability to have large structures in space (large instruments are needed to detect very rare particles). These developments are likely to occur over the next decade. Results from HEAO-C, various Spacelab missions, and the Cosmic-Ray Observatory will show which observations are most essential to astrophysical studies. Among the programs that should be studied for possible inclusion in a late 1980's mission are (1) extension of the measurement of energy spectra of individual elements up to the range of 10^{16} eV for protons and 10^{14} eV/nucleon for heavy nuclei; (2) measurements of isotopic composition of rare elements, particularly elements heavier than iron; (3) broadband measurement of the energy spectra of individual elements heavier than iron; and (4) high-resolution observation of individual elements to establish fine structure in the energy spectra.

SOLAR PROBE

An area of exploration that might prove extremely fruitful is a close encounter with the sun. Specifically, a spacecraft could survive in a perihelion passage within several solar radii to make *in situ* measurements of the solar wind (composition, magnetic fields, plasma waves), energetic particles (acceleration, storage, propagation), photospheric and coronal fine structure, dust concentration, solar mass distribution, and quadrupole moment. Also, a near-sun probe could be used as a platform for relativity experiments.

A mission of this type is potentially of high scientific interest and apparently technically feasible, although it will require more study before we can be sure of its place in our strategy.

SPECIFIC MISSION GOALS AND RECOMMENDATIONS–MODERATE MISSIONS

In addition to the major missions described in the two preceding sections (having estimated costs in the range of $\$10^8$ or more), our strategy includes programs of more modest cost and objectives. These programs are not usually in substantial competition for resources with the class of major missions. Their lower cost should not imply lower priority. The major missions and moderate missions represent two rather distinct ways of doing space experiments. Both are essential elements of an adequate and orderly exploration of the universe.

Spacelab Principal-Investigator-Class Experiments

The Shuttle Spacelab, with its initial capability of providing frequent several-week space exposure and recovery for many instruments, will be an invaluable tool for development of new detector systems and limited measurements for specific scientific objectives.

For example, new large detectors for x-ray polarimetry and spectroscopy should be proven in Spacelab flights, and at the same time new astrophysical measurements of a limited number of sources would be achieved. A large-area ($>10^4$ cm^2) x-ray instrument sensitive up to at least 7 keV with moderate resolution (about 1 arc min) could produce a sky survey far deeper than that of HEAO-1, strongly complementing the 1-2 m class X-Ray Telescope facility; the concepts proposed for achieving such an instrument at relatively low cost could be tested profitably in Spacelab flights that would, at the same time, provide the 1-arc min survey of limited sections of the sky. The hard x-ray imaging instrument could provide structural information on the non-thermal component of solar flares in the few-arc sec regime.

Likewise in gamma-ray and far-infrared astronomy, PI-class (few million dollar) experiments can provide new science as well as detector development opportunities. Given appropriate sortie-mode telescopes able to fly on Spacelab, the same will be true for UV-optical and solar experiments.

In cosmic-ray astrophysics, an experiment being built for Spacelab-2 will provide elemental abundances in the TeV/amu energy range and will be the first spaceflight application of transition radiation detectors. Other cosmic-ray experiments able to provide new science in a two-week Spacelab exposure, as well as develop new detection techniques, would include a magnetic spectrometer to measure the positron spectrum up to about 10 GeV and instruments to measure isotopic composition of neon, magnesium, silicon, and iron.

Thus, in most areas of space astronomy it is likely that the innovative techniques will increasingly be proven first on relatively inexpensive principal-investigator-class Spacelab experiments, prior to commitment of major funding for a large free-flying spacecraft. Indeed the vitality of space astronomy probably depends on continued availability of such flight opportunities to a wide community of investigators.

We recommend that a vigorous program of ongoing support of principal-investigator-class astronomy and astrophysics experiments on Spacelab be undertaken now and continued with a targeted annual level of effort exceeding that of a typical moderate mission.

Spacelab Facility Instruments

SOLAR OPTICAL-UV TELESCOPE

Many of the most interesting problems in solar physics involve processes that occur on scales of 100 km or less, too small to be resolved with earth-based telescopes. These include, among others, magnetic-field behavior on the quiet sun, dynamics of sunspots, magnetic-field structure in active regions, and properties of flares at photospheric and chromospheric levels. Moreover, each advance in spatial resolution has led to new discoveries. The Space Shuttle offers an outstanding opportunity to gather high-resolution observations of the solar surface. Since small-scale solar structures have short characteristic time scales, one does not need a large free-flying telescope. One- to two-week missions of Shuttle-based high-resolution telescopes are sufficient to do these studies and offer the advantage of frequent access by the users for the modification and installations of different attachments. A diffraction-limited optical-UV telescope of modest size (125 cm), covering the spectral range of 10^3-10^4 Å, will be a large leap forward from the present observational capabilities. Its 3-30 times improvement in resolution over that of the best existing telescopes will provide the data needed for a major advance in solar research.

We recommend that priority for the construction of Shuttle-based facilities be given to a Shuttle Solar Optical-Ultraviolet Telescope with an aperture capable of resolving at least 0.1 arc sec.

SHUTTLE INFRARED TELESCOPE FACILITY

The next step in infrared astronomy after the infrared astronomy survey satellite (IRAS) is a cooled telescope of the 1-m class with a variety of focal-plane instruments for imaging, photometry, spectroscopy, and polarimetry. Such an instrument is well suited to the Shuttle, where cryogen replenishment and instrument changes are simplified by the sortie mode of operation. The scientific potential is very great, particularly for studies of stellar formation, the interstellar medium, and extragalactic sources.

The significance of this IR telescope can be best appreciated through an understanding of the current limitations of infrared astronomy. These limitations arise directly from the thermal emission of the atmosphere and of ambient-temperature telescopes. They are insurmountable except by placing a telescope above the atmosphere and cooling it. For observations covering a broad spectral band—photometry, polarimetry, and multiplex spectroscopy—the thermal background degrades the sensitivity achievable with existing detectors by a factor of 30-1000, depending on the application, over the entire spectral region from 3 to 100 μm. Over most of this region, even a monochromator will be background-limited up to spectral resolutions of the order of 10^5. At the same time, advances are continuing in detector sensitivity at an average rate of a factor of 1.5 to 2 every year. It can therefore be estimated conservatively that the proposed telescope will be 100 to 1000 times more powerful than any competing instrument. The impact will be comparable to switching from a 12-inch telescope to the Palomar 200-inch.

We recommend that development of a meter-class, cryogenically cooled, infrared telescope be actively continued, keeping open the option of construction as a free-flying spacecraft until the Shuttle environment has been demonstrated to be sufficiently free of contaminants.

STARLAB

The Committee identified a need in the optical–UV range for the following capabilities to complement those of the space telescope: (1) a comparatively large field (>½°) with high angular resolution (0.3 arc sec or better); (2) wavelength coverage and efficient spectroscopic capability down to the spectral range λ = 940 Å, and (3) a system of general-purpose limited PI-class investigations not included on ST. These needs can be satisfied by a 1-m-class Shuttleborne telescope, assuming that it can be flown on at least two missions per year.

A high-resolution, wide-field instrument is an invaluable tool for such studies as variable stars in external galaxies and clusters of galaxies. In addition, this instrument would complement the Space Telescope by providing test facilities for new instruments and surveying wide fields to faint magnitude.

We recommend that a 1-m class, wide-field, high-resolution UV–optical telescope facility for use in the Shuttle sortie mode be implemented.

Spaceflight Duration

Nearly all astronomical Spacelab payloads, whether PI or facility class, will return results in proportion to the available observing time. Since the cost associated with extending missions is quite small compared with costs of instrument construction and Shuttle launch, it is clear that very strong arguments of astronomical productivity and efficient use of resources join to justify the following: *We recommend that priority be given to developing improved life-support systems and power modules able to support Spacelab missions with durations of up to eight weeks and, if feasible, generalized space platforms with occasional Shuttle access permitting much extended life for many of these missions.*

Explorers

The Explorer program has been one of the most fruitful aspects of NASA's space-science activity. Unfortunately, severe funding constraints have recently hampered the program. In spite of this, opportunities can be identified that represent scientific objectives of high priority; they must be incorporated as part of the space-astronomy effort. NASA has recently specified two missions to be included in the Explorer program. These are Cosmic Background Explorer (COBE), intended to survey the 3-K microwave background on large angular scales, and the Extreme Ultraviolet Explorer (EUVE), which will be an all-sky survey in the extreme-ultraviolet to soft-x-ray range extending from several hundred angstroms down to 44 Å. Ongoing Explorers include Small Astronomy Satellite (SAS)-3, International Ultraviolet Explorer (IUE), and Infrared Astronomy Survey (IRAS).

The most important candidate for a future Explorer is a long-lived (at least several years) x-ray mission of only moderate aperture and pointing capability to study time variability of sources over a range from milliseconds to years. The principal technical requirements are long life and measuring flexibility in orbit rather than great sensitivity. It must be possible to obtain both continuous runs and samples of information on a large number of sources (~100) over a wide range of time intervals. Included in this domain is the study of the pulsing x-ray sources, which offer an unprecedented opportunity to investigate the physics of neutron stars. Also included here is the study of Cygnus X-1, the most credible black-hole candidate identified so far, as well as other objects suspected to be of the same kind. Time-varying x-ray phenomena offer the best opportunity now known for verifying the existence and studying the properties of black holes with their almost unique promise of testing the limits of physics.

Beyond this mission, other aspects of x-ray astronomy appear to have high promise, particularly with regard to spectroscopy and polarimetry.

We recommend continuance of a vigorous Explorer program, with target levels of at least one launch per year. We support the individual Explorers now in the NASA program but recommend for the future a modest increase over the present budget limit for each to recognize both the effects of inflation and the growth in sophistication of instrumentation and/or pointing requirements. Priority among the new Explorers should be given to one devoted to studying time-varying phenomena in the x-ray region.

Other Moderate Missions

As in the case of the major missions, there are other moderate-mission concepts that we are not yet prepared to specify as high-priority items in our strategy. These include an ultraviolet survey telescope (approximate specifications: 75-cm aperture, $f/3$ to $f/3.5$, 4 to 5° field, 1- to 2-arc sec images, 1300–1800 Å spectral region), a prototype Shuttle sortie-mode radio experiment for very-long-baseline interferometry, a grazing-incidence x-ray solar telescope, an x-ray spectroscopy Explorer, an x-ray polarimetry Explorer, and a prototype submillimeter telescope. However, in particular, the first two of these concepts are relatively well studied and scientifically promising as early Spacelab missions and may well prove to fit into the less-expensive category of PI-class experiments.

SUPPORTING ACTIVITIES

Theory

As Chapter 3 makes clear, progress in astronomy and astrophysics depends on an effective interplay between observation and theory. This interplay must occur at several levels. Theoretical ideas provide a strong guide in the choice of experimental and observational endeavors. Similarly, involvement with experimental and observational results helps theorists to interpret the results and pose new questions that are subject to empirical test.

Support is needed for those activities that facilitate communication between theorists, experimenters, and observers. Collaboration of theorists on experimental programs should be encouraged. Similarly, support for a variety of conferences and workshops is needed; diversity of topic and viewpoint should be encouraged.

The problems posed for the theorist to solve during the next decade parallel in many respects those for the observer and experimenter: understanding planetary systems, stars, galaxies, and cosmology. However, not all areas are equally ripe for theoretical progress, and not all types of theory are of equal value. Support for theory is vital, but it is equally important to choose well which theoretical work to support. Peer review procedures are particularly valuable in this context.

Top priority should be given to support of innovative work on fundamental theory. However, such work may be fairly difficult to identify prior to its completion, so it is important to diversify support to stimulate dialogue between different viewpoints. Competition helps to clarify theoretical ideas. Other things being equal, it is better to support two smaller groups than one large one of the same size and no greater diversity. On the other hand, if a group is too small it may suffer from intellectual isolation and lack of internal criticism. Easy and frequent access to experts in similar or adjacent topics is an important stimulus to good theory.

The "innovative" work just mentioned is incomplete without "exploitative" research that works out the logical implications of fundamental theory in enough detail for comparison with experiment and observation. Although sometimes done by different theorists, this phase is really a necessary continuation of the previous one. Unlike innovative theory, it is relatively easy to identify high quality in the exploitative component of research programs.

Experimental work often suffers from a lack of good theoretical support, but the cost of such support is usually relatively small. Astrophysical systems are sufficiently complex that theoretical studies often require use of computers; price reductions brought about by minicomputer technology are greatly increasing the possibilities in this area.

In summary, support for theoretical work at several levels is of vital importance. *We recommend that theoretical work be supported concurrently and in* *parallel with the availability of new observational results, to lead to the deepest possible understanding of new finds and the most efficient guiding of new observations. This support should include the following:*

(a) *Direct support for theoretical programs of the highest quality. Research people as well as facilities need to be supported.*

(b) *Encouragement of participation of theorists in experimental programs.*

(c) *Support for a variety of high-quality conferences and workshops that facilitate scientific communication.*

(d) *Development of dedicated computational facilities to bring available computing power up to the standard of present minicomputer technology.*

(e) *NASA should make available time on its largest computers for theoretical problems of great complexity, which are often beyond the capacity of university-scale computers.*

This support should be sufficiently focused to maintain the highest quality of theoretical work and sufficiently widespread to maintain an intellectual dialogue.

Instrument Development

All disciplines are involved in developing new technologies that are essential for further progress; a number of these are noted in Chapters 3 and 4. We summarize here the currently most urgent examples of such developments:

1. Optical and ultraviolet astronomy, as well as x-ray astronomy, require support for an active program in the development of photon-counting detectors that are capable of more fully exploiting the sensitivity of focusing instruments. The point of diminishing returns is not likely to be reached until at least 75-80 percent of incident photons can effectively be counted over nearly all of the spectral range.

2. Infrared astronomy must develop highly sensitive detectors for wavelengths longer than 30 μm. Progress in this field is limited by present detector technology.

3. X-ray astronomy must further develop high-resolution telescopes in terms of achieving angular resolution of $\leqslant$1-arc sec and higher efficiency at energies greater than 7 keV; also higher-sensitivity imaging detectors and higher-efficiency spectrometers are needed for focal-plane instruments.

4. Gamma-ray astronomy has to move ahead with instruments of considerably higher sensitivity to detect sources with fluxes of 10^{-8} photon cm^{-2} sec^{-1} and angular resolution equal to or better than 3 arc min in the high-energy region.

5. Gamma-ray astronomy must develop improved spectrometers for nuclear gamma-ray spectroscopy with sensitivity sufficient to detect sources with fluxes of 10^{-6} photon cm^{-2} sec^{-1} and with good energy resolution ($\sim$0.1 percent).

6. Cosmic-ray detectors must be developed that will have the sensitivity and the resolution capability to investigate the isotopic composition of the elements throughout the periodic system, even where the abundances are extremely small. It further needs devices of large area, capable of measuring energies in the TeV range.

In the past the level of support for new technologies has in large measure determined the rate of progress in each field. It is clear that this kind of support will continue to shape the long-range future. *We recommend that a most important area to be vigorously pursued in the coming 10 years is the development of the next generation of detectors and instruments that are to be flown in the latter half of the 1980's and beyond.*

Data

Different categories are present here, respectively, the obtaining of necessary supporting data and the problem of data handling.

All experience to date indicates that many successful space-astronomy programs place a very heavy burden on ground-based observatories to locate and define appropriate candidate objects, to make or confirm identifications, to determine coordinates, and to obtain such information-rich parameters as magnitudes, colors, spectra, and polarization. This will be especially true for the Space Telescope. While the Committee's province excluded ground-based astronomy, this question is so important as to require mention here in the Supporting category, to call attention to its necessity. Thus, *we recommend that adequate funding be provided for ground-based observatories to obtain those observations that are essential to efficient operation of and interpretation of data from space-astronomy missions.*

A second category of necessary data is that which requires laboratory astrophysical investigation. In this context appear such topics as the surface chemistry of small particles at low temperatures, the microwave spectra of organic molecules, and the measurement of many pertinent atomic and molecular cross sections. *We recommend that adequate support be provided for high-quality laboratory determinations of parameters needed for the full exploitation and interpretation of the results of space-astronomy missions.*

In our discussion of the scientific rationale and disciplinary scenarios for space astronomy and astrophysics in this decade (Chapters 3 and 4), we did not specifically stress the question of data handling. Since the scientific success of any space observation requires the retrieval, analysis, and publication of data as well as the deployment of an instrument, it is important to emphasize this point.

In addition, the coming decade will see the implementation of major space observatories, requiring special centralized data centers for the user community, as well as more traditional principal-investigator-directed flight instruments. The ST will be the first large space observatory; its ultimate success will depend almost as much on the handling, management, and dissemination of data to serve the wide user community as on the capabilities and operation of the spacecraft. The organizational and management structure required to achieve this goal has been investigated in a special summer study, and we concur with the general conclusions reached in the report[1] by that group. The X-Ray Telescope facility will constitute the second major space observatory serving a large community; it may require a similar mode of operation. The increasing role of coordinated observations in widely different wavelength bands, ground- as well as space-based, will have to be an important consideration when the institutional needs for support of the X-Ray Telescope are worked out.

The data rates from the Space Telescope and the X-Ray Telescope are smaller than those collected from existing earth-resources satellites and can be handled using methods that are already state of the art.

The advent of the Shuttle will provide data rates from principal-investigator-type instruments that are much larger than individual experiments could deliver in the past. Institutions involved with Shuttle experiments must have the capability to handle large quantities of data. *We recommend that support for data retrieval and data analysis be thoroughly assessed well in advance of flight and that particular attention be given to avoid the loss of important research because of inadequate data-handling support.*

Rockets, Aircraft, and Balloons

Few, if any, NASA efforts have a better ratio of science output to expenditure than the very-low-cost rocket, aircraft, and balloon programs. Much of the science emerging from these programs is of excellent quality. Rocket science has been the workhorse for the development of optical and x-ray astronomy in space. The aircraft program is a most important tool for infrared astronomy. The balloon program was recently studied in detail by a special committee of the National Research Council[2] and found to be a highly cost-effective contributor to infrared astronomy and high-energy astrophysics. These programs provide a testing ground for instrumentation later used in spacecraft and also offer advanced students in the field of space astrophysics an opportunity for direct involvement in all stages of a scientific investigation.

We expect these efforts to continue to play an important role during the next decade, at least until Shuttle piggyback operations become simple, routine, and very cheap. Until then it is important that the present programs be maintained at a strong level and protected against inflationary erosion. Thus, *we recommend careful attention to the maintenance of effective aircraft, balloon, and rocket programs until and unless it can be demonstrated that fully adequate and cost-competitive substitutes are available.*

REFERENCES

1. *Institutional Arrangements for the Space Telescope*, Report of a Study at Woods Hole, Massachusetts, July 19–30, 1976 (National Academy of Sciences, Washington, D.C., 1976).
2. Balloon Study Committee, Geophysics Research Board, *The Use of Balloons for Physics and Astronomy* (National Academy of Sciences, Washington, D.C., 1976).

3
Status of the Science

Astronomy is a science in which exploration continues to play a paramount role. Our information about distant parts of the universe is meager, while new and unexpected phenomena are still being discovered even in the sun, in our galaxy, and in relatively nearby galaxies. Nevertheless, despite the incompleteness of our knowledge, the discoveries and the explorations are made within a general structure of belief that is shared by the vast majority of astronomers. This commonly accepted "Grand Design" may be incorrect in its details or even in its overall concept. However, it serves as a framework into which astronomers try to fit new discoveries. At the same time, the general conceptual framework may need to be modified as a result of new discoveries and theoretical insights.

It is thought by most astronomers, based on several lines of evidence, that the universe began to expand from a dense state in a "big bang" about 10 to 18 billion years ago. Among the main problems of contemporary astronomy are to assess the reality of this picture of the origin and whether the expansion will continue forever or whether the universe will collapse at some future time. Implicit in such considerations is the assumption that the laws of physics as we know them here and now also apply to the universe in the large and throughout time. One of the main results of the constant interplay between observations and theory will be to shed light on whether this is correct.

The universe is usually assumed to have been homogeneous during its early phases, with the material emerging from the hot "big bang" in the form of the simplest elements—mostly hydrogen, with about 25 percent by mass of helium-4 and traces of deuterium, helium-3, and lithium-7. At some point, this gas developed instabilities leading to the formation of galaxies and clusters of galaxies, both large and small. The galaxies then expanded away from one another unless they happened to be in sufficiently dense clusters. It appears that much of the matter in the universe condensed into galaxies and stars at an early stage. However, we have little theoretical understanding of the physical processes involved in the early phases of formation and evolution of stars and galaxies.

Stars form in galaxies at rates that somehow depend on the initial conditions in the protogalactic clouds, thus giving rise to the familiar characteristic forms of galaxies. In elliptical galaxies, most of the initial gas was consumed by star formation early, probably within the first billion years; in these objects there is little current star formation. At the other extreme, the irregular galaxies are still 50 percent gas; they are now undergoing a high rate of star formation. Between these two extremes lie the spirals, which contain an old central bulge more like an elliptical galaxy together with a disk in which star formation goes on continuously but at a lower rate than with irregulars.

The stars produce the light emitted by galaxies in the visible spectral region; the ultimate source of most of their energy output is thermonuclear reactions, which involve the synthesis of hydrogen into helium and heavier elements. A part of these synthesized elements is ejected back into the interstellar gas, either explosively as in novae and supernovae or more quietly in the form of stellar winds (the solar wind is an example of this important phenomenon in the life cycle of a star that can be studied in detail). Thus over the lifespan of a galaxy its interstellar gas becomes enriched in heavy elements, and later generations of stars are born with an increased heavy-element content. While the theory of the related subjects of stellar evolution and nucleosynthesis has been vigorously explored and many laboratory experiments in atomic and nuclear physics have been performed to obtain empirical parameters needed in the theory, it has not yet been tested sufficiently by astronomical observations. In particular, the nature of the late stages of stellar evolution has only begun to be examined in a quantitative way and has hardly been tested at all. The formation and properties of neutron stars and black holes offer enormous observational challenges for space astronomy, while their theory uses and reacts on the broad sweep of modern physics from the nature of weak interactions through hadron physics to strong-field gravity. On this preliminary framework we are beginning to construct an understanding of how galactic evolution proceeds on a large scale.

The universe contains objects—the quasars, radio galaxies, and active galactic nuclei—in which enormous amounts of energy are released in very small volumes. It is generally believed that the ultimate energy source in these objects is not provided by nuclear reactions; however, no fully convincing alternative has been proposed. The mystery posed by these objects is one of the most challenging in contemporary astronomy.

STARS AND SOLAR SYSTEM

Introduction

Stars are basic building blocks of the universe. They contain much of the matter currently known to exist. Their evolution provides a clock for determining sequences of astrophysical phenomena. The nuclear processing that takes place in their interiors is the source of most of the energy and chemical elements essential to life.

The questions of stellar evolution (how stars are formed, how they live and die) are of fundamental importance to our understanding of the universe. Our present picture of stellar evolution begins with the formation of dense, cool clouds in the interstellar medium. Such clouds are unstable to gravitational collapse and fragmentation. The collapse of a fragment causes an increase in the central pressure and temperature until the interior can support nuclear fusion. The energy released in this process permits a long period of relative stability. As successive nuclear fuels are exhausted, the star becomes progressively hotter and more centrally condensed and its evolution proceeds ever more rapidly. The end point of the process is almost inevitably a compact object: a white dwarf, a neutron star, or perhaps a black hole. These later stages are usually reached through a long period of mass loss that begins gently as a stellar wind or mass transfer but frequently ends violently as in the case of supernovae. By now the interstellar medium consists in part of material that has been cycled through a nuclear processor.

This general picture has been developed through an interplay of observation and theoretical work. Our grasp of the evolutionary sequence, however, is not uniform. While the stable burning phases are relatively well documented, the formation and the later evolutionary phases are poorly understood. Advances in these areas will again come from a blend of theory, observation, and laboratory experiment. (In this report we do not discuss the need for additional work in experimental atomic and nuclear physics.) The result will not only be a better picture of the universe based on the known laws of physics but also deeper insight into those fundamental laws themselves.

The Formation of Stars

We have witnessed only small parts of the transformation of dark interstellar clouds into brightly burning stars. The conditions at the beginning of this process are now being revealed through radio molecular line and infrared studies, which penetrate the interstellar dust that blocks our view of the cores of the densest clouds. The identification of a large variety of molecular species in these clouds has been one of the dramatic successes of modern astronomy. Another important result has been the discovery of compact infrared sources buried in molecular clouds—stars in the very process of formation. These sources appear to be about to burst out of their surrounding dust cocoon, after which they will presumably resemble the young emission-line stars studied at optical wavelengths and heretofore the youngest stars known. At the same time, planetary studies (including comets, asteroids, and meteorites) are beginning to provide tests of theories regarding the condensation of solids in circumstellar shells.

COOL INTERSTELLAR CLOUDS

The steps leading to the formation of very dense, cold clouds and the stages by which such clouds fragment and collapse to form hot but still cloud-embedded stars are essentially unobserved. Observational data are crucial to theoretical discussions in this area because the behavior of low-pressure material, such as cold interstellar clouds, is particularly difficult to treat theoretically.

It is expected that the core of a molecular cloud will be at a temperature of about 10 K at the beginning of its fragmentation and collapse into protostellar condensations. As the condensations evolve, they will warm until their outer layers reach temperatures of a few hundred degrees, typical of the compact infrared sources already under study. Thus, observation of the earliest stage of stellar evolution is dependent on the development of sensitive measurement techniques for the far infrared (30 μm to 1 mm), the spectral region corresponding to peak emission for temperatures between 3 and 100 K. Intensity and velocity maps are required in a number of lines to determine the environment in which collapse and star formation begin. Among the questions to be answered are the following:

1. How does the level of fragmentation depend on mean density?
2. What are the roles of magnetic fields, turbulence, and rotation—do clouds collapse to disk structures first?
3. How is the magnetic flux rearranged as the condensation becomes a star?
4. What is the state and composition of the material, and how does this affect fragmentation? In particular, what fraction of the material is in the form of molecular hydrogen (H_2)?
5. How can star formation proceed in young galaxies as compared with a thoroughly worked-over system like our present galaxy?

The dynamics of these clouds can be studied provided velocities of a few kilometers per second can be measured; this would require spectral resolution of $R = 10^4$-10^5 ($R = \lambda/\Delta\lambda$). Observations of many lines (corresponding to different excitation levels) will differentiate among different temperature and density regions in the clouds. In order to study the later stages of the fragmentation process, high angular resolution measurements are needed, capable of measuring structures on a scale of a few astronomical units (AU).

Attainment of these goals involves substantial improvement in our instrumental capabilities. The highly developed techniques for molecular line studies in the microwave region can be profitably employed on larger ground-based telescopes. Ground-based interferometers are needed to achieve high angular resolution at wavelengths between 1 mm and 1 cm. Techniques to study molecular lines in the infrared region are relatively poorly developed, despite the expectation that many important lines will be found there (such as those of molecular hydrogen and of nonpolar molecules like CO_2 and CH_4). A large, cooled, spaceborne telescope, which will eliminate the problems of atmospheric emission and absorption and of instrumental emission, will be required to measure the spectral lines at sufficiently high resolution. This will dramatically expand the results on dense molecular clouds now being obtained in the microwave region. The diffraction limits of even the largest telescopes in the infrared are inadequate to probe the dust emission of collapsing clouds on the necessary scale of structure. For example, the diffraction limit of a 5-m telescope at 20 μm corresponds to about 500 AU at the distance of the Orion nebula, yet the structures that we wish to study are only a few AU in size. The higher resolution achievable by large, spaceborne, spatial interferometers is likely to become of crucial importance in studies of protostellar collapse and of the formation of planetary systems.

Finally, the determination of chemical and isotopic abundances within the solar system is a powerful method to probe the composition of and conditions in the protosolar nebula. For example, recent work on meteoritic abundances, particularly the anomalous abundance of ^{26}Mg, suggests that the protosolar nebula contained short-lived radioactive species (e.g., ^{26}Al), perhaps indicating a nearby supernova explosion only a few million years or less before the formation of the sun.

PROTOSTELLAR SOURCES AND PRE-MAIN-SEQUENCE STARS

Once the condensing cloud fragments become opaque, their rapid collapse ends and subsequent evolution is determined by diffusion of energy to the surface permitting a steady contraction and increase in internal temperature. This process is halted when temperatures become high enough to sustain nuclear reactions.

Some of the problems associated with this phase of star formation are the following:

1. What is the mass spectrum of young stars, and how does it depend on

initial conditions such as magnetization and turbulence and the state and composition of the matter?

2. What fraction of the material ends up in stars, and what fraction is dispersed?

3. Does the formation of the first stars result in further waves of star formation or in cessation of the process?

4. What is the age spread of stars formed in clusters?

5. Do stars of the same mass approach the main sequence along a well-determined evolutionary sequence?

6. How are binary stars formed?

7. How and when do solar type stars lose their angular momentum?

8. How do planetary systems form? How much of the complex molecular content of the cool clouds remains during the formation of planets?

9. To what extent does complete mixing of the nebular material occur before solid bodies form?

For stars still embedded in dust and gas, these studies will be mainly at infrared wavelengths and will demand moderate to high resolution (10^3-10^5) spectroscopic capability.

After they emerge from dust clouds, pre-main-sequence stars can be studied in the visible and ultraviolet regions. Extensive work has already been carried out on Herbig-Haro objects, T-Tauri stars, and other young stars. As a result, parts of an evolutionary sequence have been suggested, but this area is one of continuing controversy. A combination of high-resolution radio, infrared, optical, and ultraviolet measurements will be required to study the physical state and velocity fields within H II regions of varying degrees of compactness and age. For compact H II regions, higher spatial resolution will provide key evidence on ionization structure. Polarimetric measures will also be valuable in delineating magnetic-field structure.

Studies of the nature of cometary and meteoritic material; of the internal constitutions and surfaces of the planets, satellites, and asteroids; and of the evolutionary forces that have shaped the solar system since its formation can provide important insights into the birth process of the solar system and stars in general. Space observations may be able to provide direct evidence of the presence of planets around stars either by astrometric observations of the star in the visible (positional accuracy = 10^{-3} arc sec) or possibly by direct detection of the planet in the infrared (where the brightness ratio, particularly for a "protoplanet," is more favorable).

Stable Phases

Stars spend by far the largest fraction of their lifetime in stable configurations, drawing on nuclear-energy supplies to maintain their energy output. It is not surprising, therefore, that this phase is better understood than others, in part, because of extensive but still incomplete laboratory experimentation in atomic and nuclear physics. Since the sun is also in this phase and can be studied in far greater detail than other stars, it plays a key role in stellar research. Most of the phenomena observed on the sun are known to have analogs in other stars. Because these phenomena may be more extreme in other stars and because other stars can be studied statistically, stellar astronomy can frequently provide insight into solar phenomena. The relationship between solar and stellar science is so close that we have chosen to consider these together even though the observational techniques are quite different.

The solar and stellar studies outlined below will not only solve many important astrophysical questions but also are likely to have major practical applications as well. Evidence is growing that the sun is implicated in major climate variations on time scales ranging at least from years to centuries. In a world so precariously balanced with regard to food supplies, and where human activities are also beginning to have large-scale climate impact, it has become imperative that we understand in accurate detail how the sun works as a star, why it changes, and what are the predictable and understandable consequences for the earth.

THE EVOLUTION OF STARS

The basic picture of nuclear processing during the stable phases of stellar evolution derives from observations of globular and open clusters and uses the knowledge of the sun and nearby stars to provide calibration of these data. It is of fundamental importance to check and further develop this picture not only because it refers to the state of much of the matter in the universe but also because it provides the key to many other problems in astronomy, for example, the state of the interstellar medium, the evolution of galaxies, and even the determination of the rate of expansion of the universe.

Major questions in this area concern the effects of initial chemical composition and the degree to which nuclear processed material can be redistributed within the star, particularly brought to the surface, and in general the accuracy with which modern computations can model the interior structure of stars. The only direct probe of the interior conditions known at present is the solar neutrino flux. Several less direct but more widely applicable methods are available, among which are the following:

1. The classical approaches involving tests of the predicted relations among stellar mass, luminosity, surface temperature, and surface composition;
2. The study of stellar pulsation, which may also be extendable to the sun if the global oscillations are confirmed;

3. The study of surface-composition variations from place to place on a given star, between stars of the same evolutionary phase (as in globular clusters), and among stars of different evolutionary phase;
4. The study of large-scale solar and stellar surface currents that reflect interior circulation;
5. The study of the origin of solar and stellar activity cycles.

The main observational requirements are to obtain more accurate distances, more accurate luminosities, and more detailed spectra.

Observations from space can provide an order-of-magnitude improvement in angular resolution and hence, in a given time, comparable improvement in parallax and proper motion data. These data are fundamental for determining distances and luminosities of stars and clusters, which in turn are fundamental for extending the distance and luminosity scales out to the universe. Luminosity and color (or very-low-resolution spectrophotometric) observations in dense or distant clusters also require improvement, especially for lower mass stars and particularly for stars that are significantly hotter or colder than the sun, where the emission is concentrated, respectively, in the ultraviolet or infrared. Observations from space are, of course, required for the ultraviolet; but for faint stars, space observations will permit more accurate luminosity determinations even in the visible because of reduced sky background and confusion problems. Among more important examples, the horizontal branch stars in the Magellanic Clouds come into view at around visual magnitude 20. At least a further 3-5 magnitude penetration is required to reach the lower main sequence of globular clusters.

Studies of surface composition require at least intermediate-resolution spectroscopy; useful results can be achieved with $R > 10^3$, although the range $10^4 < R < 10^5$ is desirable. It is important to determine abundances in, for example, the lower main-sequence stars of globular clusters in order to obtain a better estimate of the initial composition at the time the galaxy formed, which in turn has deep cosmological implications. For such work, a very large telescope is required. Isotope studies in late-type stars, which are key indicators of mixing and nuclear processes, are best carried out by studying molecular transitions that occur mainly in the infrared. Again, resolutions of 10^4-10^5 are desirable. Except where angular resolution is required, much of the abundance work on normal stars is best done in the visible and near IR (i.e., from the ground). However, the UV can provide better information on very-low-abundance species, and knowledge of the UV continuum is frequently essential in interpreting the data. Likewise some of the important IR spectral features will require extra-atmospheric observations in order to avoid terrestrial absorption bands.

CIRCUMSTELLAR MATERIAL AND MASS LOSS

The existence of circumstellar material and stellar winds has been recognized for some time. Detailed information is available for the sun, where the mass loss is thought to arise from heating of the circumstellar envelope (corona) to thermal velocities comparable with the escape velocity. The mechanisms involved in heating the corona and chromosphere, while not fully understood, are apparently associated with the conversion of mechanical into thermal energy through some combination of magnetohydrodynamic, sound, or other waves arising from turbulent activity at photospheric levels. It is likely that most late-type stars have associated coronas and winds caused by similar mechanisms.

More substantial mass loss is known to occur in early-type stars, where the driving mechanism is thought to be radiation pressure in ultraviolet resonance lines. It appears that major mass loss also occurs in giants, where the mechanism is uncertain, and in late-type supergiants as a result of radiation pressure on dust formed in the stellar atmosphere. In both cases the loss rates are much higher than for the sun and can have a significant effect on the evolution of the star. Finally, certain rotating stars—the dwarf Be stars—appear to be losing matter because of increasing rotational instability as the star evolves.

In the study of thermal and pressure-driven (solar-type) winds, the main focus of activity must be the sun. It will be necessary to determine the energy transport mechanisms from convection zone to corona, and the detailed structure of the solar envelope (corona and wind zones). Space observations have led to dramatic progress in several of these areas: coronal holes associated with open magnetic regions, exceedingly high-temperature regions in the corona, and the remarkably rapid rise to coronal temperatures over a distance of a few hundred kilometers. The rich EUV spectrum of the chromosphere and corona is also leading to a wealth of data on atomic and transport processes in these regions. There remain a number of major questions, e.g.,

1. Precisely what heats the corona, and how?
2. What causes the coronal holes to be different from the rest of the corona?
3. What drives the high-speed streams?
4. What is the significance of magnetic-field configurations and magnetohydrodynamic waves for the dynamics of the coronal holes?
5. How do magnetic-field fluctuations propagate outward and interact with the earth's magnetosphere?

The scale height of the photosphere and chromosphere is 100–200 km. Major physical changes occur over such distances, or at a scale of 0.25 arc sec.

The best ground-based observations, however, are sporadic and limited to the photosphere. Major progress in understanding the energy transport is to be expected from time sequences of photospheric–chromospheric–coronal observations from a large-aperture optical–ultraviolet telescope with a spatial resolution of 0.1 arc sec and a temporal resolution of 1–10 sec. High-resolution spectroscopy ($R = 10^5$–10^6) is necessary to resolve spectral lines resulting from different heights and temperatures and to measure velocities and magnetic fields with accuracies sufficient to discriminate between theories. In the outer corona, where the solar wind originates, major progress is expected from coronagraphs using the intense L-α emission from the small fraction of neutral hydrogen atoms present. Line-shift and line-profile measurements will lead to velocity and temperature data in this region.

Studies of other stars, in particular of the chromospheric and coronal emission lines in the ultraviolet spectra of late-type stars, will also be of value in determining the range of such activity and hence of wind strength. The potential of such data has already been demonstrated by rocket and satellite observations.

Although the sun affords the only direct means of sampling the particles and magnetic fields in a stellar wind, observations so far have been confined to the ecliptic plane. A program of coordinated observations (solar wind, magnetic fields, energetic particles) involving an out-of-the-ecliptic probe, coupled with coronal observations over a wide range of wavelengths, should be carried out soon. The passage over the solar poles should coincide with a period of minimum solar activity when coronal observations show the largest latitude variation, when earth-orbiting probes show the largest temporal variability in the solar wind, and when the solar polar magnetic fields appear to be open, permitting the best chance for nonsolar cosmic rays to penetrate into the solar environment. Out-of-the-ecliptic and any close-sun probes should carry a wide range of sensors to detect electric and magnetic fields, velocities, mass, charge, and energy of particles ranging from thermal solar-wind particles to relativistic cosmic rays. Isotopic and ionic composition are of special interest. A time resolution of a few seconds is sufficient for all of these measurements. Simultaneous observations by an out-of-the-ecliptic probe and a near-earth probe will add substantially to the exploration, especially if a white-light and L-α coronagraph, an x-ray telescope, and a low-frequency radio burst antenna can be included. These will measure the outer coronal electron density and temperature, the inner coronal structure, and the interplanetary magnetic-field configuration.

Observations with the *Copernicus* satellite have given some indications of the variation in mass loss rate and ejection velocity with temperature and absolute luminosity for objects on and above the main sequence. The sensitivity of *Copernicus*, however, is not adequate to observe many objects of interest, such as stars embedded in dense clouds, or eruptive variable stars in binary systems, which are known from ground-based visible measurements to exhibit exceptionally large and/or highly variable rates of mass ejection. This work requires spectroscopic resolution $R \geqslant 10^3$ and should reach at least $m = 15$ to allow studies of, for example, blue horizontal-branch stars in globular clusters.

Mass-loss processes and the circumstellar material in late-type stars have been studied mainly through the presence of dust, which gives rise both to emission in the infrared and to polarization in the optical. Infrared measurements from space, with high angular resolution and with higher sensitivity than achievable from the ground, will permit determination of the sizes, temperatures, and mass distributions in circumstellar dust shells ejected by normal stars in their late evolutionary stages. It now appears likely that interstellar dust originates in these stellar ejecta. It is therefore of importance to compare the properties and composition of circumstellar dust particles with those in the vicinity of newly formed stars and in the general interstellar medium. It is also important to search for molecular transitions to determine the physical state of the circumstellar gas. These measurements will require high spectral resolution (preferably $R \geqslant 10^4$) and high-angular-resolution (0.1-arc sec) measurements of spatial distribution.

FLARES AND SURFACE NUCLEAR REACTIONS

Although flare activity on the sun has been studied for many years, the flare mechanism is still not understood. Events like flares are now known to occur on other stars, most dramatically on flare stars. Further progress requires study of at least three related major problems:

1. The storage and release of energy;
2. The origin and coupling of the hot (10^7 K) plasma to the magnetic field;
3. The nature of the processes that accelerate electrons, protons, and heavier nuclei to relativistic energies.

From solar studies it is known that the flares include a slow preheating growth phase, a catastrophic magnetic-field energy release that heats the gas and accelerates particles, an expansion phase in which further acceleration occurs, and finally a cooling accompanied by particle emissions, coronal transients, and other plasma ejections. Observations of hard x rays, gamma rays, radio bursts, and interplanetary electrons and nuclei show that a substantial or even major fraction of the flare energy is converted to energetic particle flux. It is now known that all H-α flare events are accompanied by a 10^7 K plasma and probably accelerate particles.

Study of solar flares goes to the heart of fundamental problems in plasma physics: coupling between magnetic and velocity fields, heating and cooling of plasmas, and nonthermal processes. Insight gained here will be invaluable to our understanding of acceleration processes elsewhere in the universe, and the study is of direct practical importance because of the terrestrial effects of flares.

Attempts to understand the flare mechanism will continue to concentrate most heavily on the sun. The first step in a coordinated space attack on flare phenomena is the Solar Maximum Mission (SMM) now being developed.

Here new instruments will determine the location and size of the emitting region of quasi-thermal plasma (10–20 keV to 8 arc sec for large events). Gamma-ray line and continuum emission will be measured, permitting study of the dynamics of energetic nuclei near the acceleration region. Observations in the EUV and XUV will determine the evolution and structures of hot plasma, and the motion and magnetic field of this plasma, with greater time and energy resolution than previously available. An SMM coronagraph and the International Sun–Earth Explorer (ISEE) satellites will study the effects of solar flares in the extended solar envelope out to the earth's magnetosphere. The high-energy observations, simultaneous with the SMM on occasional events, will considerably enhance that mission and will initiate the scientific and instrumental developments required for continued progress during the 1980's, leading to another coordinated program during the following solar maximum (about 1990).

There is a need for studies of the particle bursts associated with flares, especially the ^{3}He-rich flares, in which the ratio ^{3}He/^{4}He can exceed unity for MeV particles. This is particularly remarkable because there is no evidence for accompanying spallation products such as deuterium or tritium. These events and the Fe-rich flares, neither of which is currently well understood, may result from a complicated interplay between spallation and acceleration processes, from an unusual injection process, or from some currently unknown process. It will be important to determine the isotopic composition of the nuclei emitted in the flare process. Such observations require large-area particle detectors (300 cm^2). Higher-resolution EUV and x-ray imaging (~1 arc sec), combined with spectroscopic studies to determine the ionization structure, should provide further insight into the flare phenomenon. A search for solar neutrons (sensitivity 10^{-3} cm^{-2} sec^{-1}) and higher-resolution gamma-ray spectroscopy ($R = 10^3$, sensitivity 10^{-3} cm^{-2} sec^{-1}) must also be planned.

Although these observations, as a coordinated program following the SMM concept, cannot be implemented until the late 1980's, significant steps should be accomplished in the early Shuttle era. These include imaging of hard x rays, increased sensitivity for gamma rays, and further study of small-scale dynamics of hot plasma from EUV observations. Of particular interest during flares are observations of structures and morphological changes with

0.1-arc sec resolution in spectral lines originating from 5000 K to 20×10^6 K plasmas.

Studies of other flare stars should yield important information on the evolution of activity after star formation, including the correlation of general magnetic-field strength and rotation velocity with chromospheric and coronal line strength. Spectroscopic requirements in the UV and visible regions are $R = 10^3$–10^5, but considerable gains in sensitivity will be required to study adequate samples. Observations should be correlated with radio and x-ray measurements.

An essential complement of this observational work is a strong theoretical effort to provide a basis for understanding the complex data that will be acquired over the next decade.

MAGNETIC FIELDS AND THEIR INTERACTION WITH PLASMAS

Most stars, including the sun, have relatively weak ($< 10^2$ G) average surface magnetic fields, although there is a well-defined class of A and B stars with peculiar surface abundances and magnetic fields often in excess of 10^4 G; the distribution of field strengths among such stars is bimodal. No satisfactory explanation exists as to the origin of these fields. The influence of magnetic fields on surface composition, convection, rotation, and structure also requires elucidation.

Although the general surface magnetic field of the sun is weak (about 1 G), it is highly structured and in localized regions can reach values in excess of 10^3 G. The 11-year cycle of solar activity is principally a cycle of magnetic variation. Phenomena such as active regions, sunspots, and magnetic knots all involve the interaction of dense, partly ionized plasma with magnetic fields driven by motions apparently just below the photosphere. These motions include the supergranulation, granulation, giant cells, and differential rotation. Major unresolved problems include the following:

1. The origin of the activity cycle;
2. Understanding the hydromagnetic effects in sunspots;
3. Interpreting the interesting phenomena of magnetic knots in which kilogauss magnetic fields are found in sub-arc-second regions;
4. The occurrence of solar flares.

Current attempts to understand the 11-year cycle generally concentrate on dynamo processes. So far, however, we have no more than simple and incomplete models. The possible variation of the "solar constant" with activity is of particular importance in view of the long-term fluctuations of the 11-year cycle and their possible terrestrial effects.

Space observations can contribute particularly to furthering our understanding of the sunspot and knot phenomena. Here photospheric and chromospheric brightness, velocity, and magnetic-field structures need to be measured in the optical-UV region with a resolution of ~0.1 arc sec, while transition regions and lower coronal structures need to be measured to better than 1.0 arc sec with EUV telescopes. Defining the physics of the heating process and of the mass motions requires determining intensities and profiles of selected EUV lines to $R = 10^5$. Superheated regions are indicated by soft (<1 keV) x-ray emission. Determination of the temperature profiles and emission measure of these features will need high-resolution (<1 arc sec) measurements of soft x-ray spectra. Possible variations of the solar luminosity will require periodic spaceflights with a solar spectral irradiance monitor with an accuracy over the integrated spectrum of better than 0.1 percent and over selected UV and EUV regions to better than 1 percent. Continued synoptic observations from the ground are needed to determine the long-term behavior of active regions, sunspots, and large-scale mass flows.

Observations of chromospheres and coronas of other stars, especially those of later spectral type, also reveal activity cycles. Such observations, combined with the observation of stellar rotation, are of particular interest for understanding the origin of the activity cycle. Although progress has been made from ground-based observations, measurements in the UV will provide better indicators of such activity. It should also be possible to observe directly the "star spots" and related phenomena in a number of red supergiants using high-angular-resolution filled-aperture telescopes, or interferometers. The origin of the large fields in certain stars could perhaps be determined by measurements of magnetic fields in protostars, presumably in the near infrared.

BINARY STARS

More than 50 percent of nearby stars are members of binary or multiple systems, although there appears to be considerable variation in binary frequency among different stellar populations. The origin of binary systems is still in dispute but could be elucidated by the study of rotational velocities in protostars. Studies of binary stars at higher angular resolution (≤ 0.1 arc sec) will provide an immense increase in the number of orbital and mass determinations. These data are essential to our understanding of stellar structure. In close binary systems, mass exchange can greatly affect stellar evolution. The amount of mass and angular momentum loss from such systems is only poorly estimated. The situation would be improved by more detailed absorption-line studies in the UV ($R = 10^3$–10^4). Similar remarks hold for studies of mass loss from late-type stars that have companions of earlier spectral type.

Later Stages of Stellar Evolution

Stars have an "energy crisis" either when available nuclear fuel is exhausted (material is synthesized to iron) or when further contraction and heating is prevented by the buildup of electron degeneracy pressure and further nuclear fuels cannot be ignited. Electron degeneracy in the interior of moderate- or low-mass stars plays an important role in determining the course of stellar evolution. The maximum mass that can be supported by electron degeneracy pressure is about 1.5 solar masses. For neutron stars, the limiting mass may be as high as 3 solar masses. More massive stars must therefore either shed matter during the course of evolution or, according to general relativity theory, be crushed by gravity, becoming black holes.

Studies of the later stages of stellar evolution are now focusing on problems such as the following:

1. What happens when more than a few solar masses of material end up in the stellar remnant? Does a black hole form as predicted by general relativity theory?
2. What are the main-sequence mass ranges that give rise to white dwarfs, neutron stars, and black holes? What are the mechanisms of formation of such compact objects?
3. What processes of nucleosynthesis occur during formation of these remnants? How much material is returned to interstellar space? What is the state of the returned matter?
4. What are the mechanisms by which charged particles are accelerated to relativistic energies?
5. What are the physical characteristics of the remnants, and what influence do they have on their surroundings?
6. What are the abundances of the different types of remnants?

These observational questions are crucial not only to our understanding of other aspects of astronomy but also to our knowledge of fundamental physics. For example, the compact objects provide perhaps the only place for testing gravitation theory in strong fields and for probing the properties of matter at extremely high density.

Observations of both the compact remnants and of the ejected material are essential. Any material falling onto such a remnant can reach a high temperature and produce photons of high energy, especially in the x- and gamma-ray range. The number of observed phenomena associated with the later phases of stellar evolution are many, and their interconnection is not at all clear at present. In some cases (e.g., the x-ray bursters and the gamma-ray bursts), virtually nothing is understood about the mechanisms involved.

WHITE DWARFS

Substantial advances have been made in our knowledge of intermediate-temperature white dwarfs. The local space density and space motions are reasonably well known. The masses of white dwarfs are typically 0.5 solar mass, although they are found in clusters (e.g., Hyades, Pleiades) that contain evolving stars of mass exceeding 2 solar masses. Thus, it appears that at least some stars having original mass of at least 3–5 solar masses can shed enough to end up as white dwarfs and hence that as much as 80 to 90 percent of the matter ejected from a generation of stars can come from those ending up as white dwarfs. The mechanisms of mass loss are poorly understood but certainly include transfer in binary systems and the formation of planetary nebulae, the central star of which often appears to be a young, very hot white dwarf.

White dwarfs have other characteristics that are not yet understood. For example, we find magnetized white dwarfs ($>10^6$ G) and unmagnetized white dwarfs ($<10^3$ G) with few, if any, intermediate cases. Some show complex periodic light variability on the scale of minutes with no evidence for periodicities in the 5–10 sec range that is believed to be the fundamental vibrational period. Most white dwarf atmospheres are "monoelemental," while some have pure continuum spectra. White dwarfs are known to be members of binary systems and appear to be involved in a variety of systems where mass is being received from a companion. This probably accounts for the various classes of cataclysmic variables and some x-ray sources. Quite recently, quantitative theories of accretion by both magnetic and nonmagnetic degenerate dwarfs have been developed and used for source identification. Novae are thought to be due to nuclear reactions in matter accreted onto white dwarfs, again probably in binary systems.

Future research should involve the following:

1. Identification of a number of compact x-ray sources as accreting degenerate dwarfs, both magnetic and nonmagnetic, using spectral and luminosity observations to determine the mass and magnetic field of the dwarfs involved.
2. Improving our knowledge of the space density of very hot and of very cool white dwarfs, including those too cool and faint to be detailed by their optical emissions. Soft x-ray and UV survey data will be required of the hot stars, and proper motion and other surveys for the cool ones. Distance determinations will be crucial at both temperature extremes.
3. Investigation of the mass range of white dwarf progenitors. This work will focus on young clusters and ideally requires very accurate motions to determine cluster membership. In most cases sensitivity to $m \geqslant 20$ is required with proper motions of $<10^{-2}$ arc sec/year.

4. Documentation of the events (e.g., dust formation) taking place in the mass loss process in planetary nebulae, novae, and the like.

THE NATURE OF SUPERNOVAE

In at least two cases (Crab and Vela), neutron stars formed during the cataclysm of a supernova explosion. The collapse of more massive cores may lead to black holes. Supernovae may well be the most significant source of interstellar material that was processed in thermonuclear reactions, and they or their remnants may be the sites of acceleration of the bulk of cosmic rays.

The following observations are likely to yield fruitful new data on supernova processes:

1. Extensive surveys of x-ray and gamma-ray sources and identifications of optical counterparts. These data may allow us to define precisely the evolutionary track of the source (neutron star, black hole, or whatever) and lead back to the supernova. Furthermore, chemical abundance anomalies in the source may be traceable to the presupernova state.
2. Ultraviolet and x-ray observations of the supernova outburst. Chemical abundances of supernova ejecta are not well established nor are the nuclear processes that produce those abundances; high-resolution ultraviolet and x-ray spectra may yield more definitive information than has been obtained so far.
3. Observations of the light curves and spectra of supernovae to a factor of 100 lower luminosity. The distance to which supernova surveys can be compiled would thus increase by a factor of 10, and light curves for nearby supernovae would be extended.
4. Gamma-ray observations of the supernova outburst with detectors of sufficient energy resolution to observe nuclear gamma-ray lines. For example, the nucleosynthesis of iron-group elements is expected to occur in supernovae. Fusion tends to form nuclei with equal numbers of protons and neutrons. These nuclei are unstable toward electron capture or positron emission and their daughter nuclei emit gamma-ray lines as they decay from excited states. An important example is the decay: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$.
5. Measurement of the isotopic abundances in the cosmic rays. These abundances should provide direct evidence for conditions in the star preceding and during the explosion, in particular abundances in the iron group probe the critical region near the theoretical "mass cut" that separates infalling from expelled material. These isotopic abundances would not be influenced by possible atomic effects (ionization potential) in the acceleration process and so would directly probe the nuclear processes. Also, the abun-

dance of certain radioactive isotopes provides a time scale between synthesis and acceleration of the particles.

6. Observations of π^0 gamma rays with sufficient angular resolution to resolve individual supernova remnants would show whether these objects are sites of nuclear particle acceleration, just as observation of the characteristic synchrotron emission has confirmed supernova remnants as sites of electron acceleration.

7. Measurement of individual cosmic-ray elements heavier than iron would indicate whether the accelerated material originates deep inside the supernova (abundances would be enriched in elements formed in *r*-process nucleosynthesis) or from the outer parts of the star.

8. Assuming that most of the cosmic rays (0.1–10 GeV/amu) are accelerated in supernovae or their remnants, the acceleration theories would be constrained if we knew how high in energy these supernova-origin cosmic rays extend; to test the range of cosmic-ray energies from this type of source, the elemental abundances need to be extended to significantly higher energies than the 100 GeV/amu to which measurements have been made.

NEUTRON STARS AND BLACK HOLES

Neutron stars are of the highest interest to nuclear and condensed-matter physicists as well as to astrophysicists. These objects have masses comparable with that of the sun with radii 10^5 times smaller, hence their densities range up to more than 10^{14} times that of typical solar or terrestrial matter. The equation of state of their interiors requires, for its development, relativistic many-body theory and the most advanced concepts of hadron physics. Theoretical advances over the past decade have shown the importance of comparing maximum mass calculations with observations, the likelihood that hadron superfluidity exists in neutron stars, and the possibilities for determining details of neutron star structure from such observations as period changes observed over extended periods of time. Hard x-ray spectral observations imply the first direct measures of magnetic fields in the range of 10^{12} G. Because of the intense gravitational field, the full theoretical treatment of neutron-star structure involves general relativity theory in an essential way. It is apparent from all of these remarkable properties that neutron stars offer a unique testing ground for our understanding of the fundamental laws of nature.

Neutron stars were discovered as radio pulsars, one so far having been shown to be in a binary system. Four of these (including the Crab and Vela pulsars) have been detected even at gamma-ray energies. A second extremely important group of pulsars includes those discovered as x-ray sources. All of these appear to be members of close binary systems, where the x-ray emission seems to be a consequence of mass transfer to a magnetized neutron star.

Theories of accretion onto a neutron star from a rotating disk give insight concerning the spin-ups observed in the eight pulsating x-ray sources for which period changes have been determined.

The pulsed radiation signature so far permitting the discovery of neutron stars arises from the presence of an intense magnetic field. Nonmagnetic neutron stars could be identified in binary x-ray sources or possibly from proper motion and brightness measures for very nearby stars. The mass range of stars producing neutron stars can be probed either through studies of binary systems or studies of young star clusters. Searches of other galaxies would be profitable in this context, at least for the x-ray sources. In all cases, high-sensitivity survey work coupled with subsequent detailed observation is required. Observation from above the earth's atmosphere would be especially important for proper motion studies of objects in the apparent magnitude range 20–25 and is mandatory for x-ray work.

The good fortune of finding more than a dozen pulsing x-ray sources (and one radio pulsar) in binary systems permits a determination of neutron-star masses. Values have been found to lie in the range of about one to three solar masses, but only Her X-1 has a precision even as good as 20 percent. Many more need to be found, and the precision must be improved. Deeper surveys to locate candidate objects and more detailed studies with appropriate pointing telescopes appear to be the best way to increase the sample and the information about each.

The pulsating x-ray stars both radiate and speed up because of accretion to their surfaces. Conversely, the radio pulsars are losing rotational energy and slowing down, deriving most of their energy from their spins. Both types show changes in their pulse period on short time scales. These data yield invaluable information about internal properties such as the presence of neutron and proton superfluidity within the stellar core, the relative moments of inertia of the solid crust and the superfluid, and properties such as viscosity or lattice structure. In all cases the physical processes are likely to be extraordinarily complex.

The rotating, magnetized neutron stars are thought to be powerful accelerators of particles and could be responsible for much of the cosmic radiation. Gamma-ray data may yield information on this possibility through the observation of π^0 decay products.

So far, we do not have any object that establishes the existence of black holes as convincingly as Sirius-B did for white dwarfs or the Crab pulsar did for neutron stars. Although distinguished skeptics still remain, most theoreticians now believe that black holes must exist and be produced under conditions that seem fairly reasonable and common in the galaxy. However, it may prove difficult to find conclusive direct evidence of their existence. What can and must be done is to search for objects so massive and compact that, under the current standard laws of physics, they could only be black holes, and then systematically study the properties of such objects both observationally and theoretically. A most interesting object is the x-ray source Cyg X-1. Its mass seems to be well above the limit for a neutron star. If in addition this object is compact, as seems to be demanded for material falling into it to be heated enough to produce x rays, then general relativity theory says that it cannot be stable—the object must be collapsing to or already be a black hole. It will be of the highest interest to seek more of such objects and to map out their properties including variability—on long as well as short time scales—of the flux and polarization in x-ray, gamma-ray, UV, optical, and any other observable wavelength.

MASS TRANSFER AND ACCRETION DISKS

Mass transfer between components in binaries is a pervasive feature of these stellar systems. Its presence changes the evolution of stars and leads to dramatic phenomena, such as the optical novae and the strong x-ray sources. If the binary contains a compact star, the process can be particularly spectacular because material can be strongly heated by falling into the deep gravitational potential well of such objects. Indeed, for neutron stars and black holes the luminosity could readily attain a value of order 10^{38} erg/sec, the upper (Eddington) limit for a steady-state spherical stellar configuration of one solar mass. The problems of mass transfer, the formation of accretion disks, the redistribution of mass and angular momentum, and the influence on the evolution of the stars have been discussed briefly above. The compact objects offer potentially the best laboratory for studying this process because the material being transferred can be observed most readily and because the presence of high-frequency clocks (the x-ray pulsars) provide powerful probes of the system dynamics.

NATURE OF TRANSIENT PHENOMENA

Most of the transient x-ray sources appear to be x-ray analogs of ordinary novae. Strong x-ray emission suddenly occurs in an otherwise very weak x-ray source. The emission persists and shows short-term periodicity on a time scale of minutes. The bursters exhibit distinctive pulses of x rays, typically with a rise time of 1 sec and a decay time of many seconds. The duty cycle is usually very low; individual bursts may only occur once every several hours, and a given source may go for long intervals without emitting any bursts. We are probably seeing episodic accretion by neutron stars, with an energy production mechanism that may be either gravitational or thermonuclear. One remarkable variety is the "rapid burster" that emits pulses more or less continuously. In many cases, a steady underlying x-ray source is found. No burster has been identified optically, but it is remarkable that perhaps half a dozen are apparently located at or near the center of globular clusters.

The gamma bursts may be a special class of the x-ray bursts. They have similar time profiles but are much more intense, showing a very hard spectrum extending to at least 1 MeV, and are much rarer.

Until now, these phenomena have been uncovered almost by accident. New observations will require especially designed instruments flown as part of dedicated missions. Many of these objects must be discovered for statistical studies, with more accurate positional data to permit optical identification. In the case of such transients it is important that their discovery be reported promptly to allow the opportunity for observations at other wavelengths. The need for coordinated data is crucial here. These transient sources may be manifestations of new astrophysical phenomena, and their discovery provides an example of the surprises that occur whenever a new wavelength or sensitivity range is explored.

The x-ray bursters offer another excellent example of new observations revealing wholly unexpected phenomena. Most of these bizarre objects may turn out to be something as "ordinary," if complicated, as plasma phenomena in the atmosphere of a magnetized neutron star. Conceivably in some cases they are signaling the presence of a black hole. Of particular interest is the presence of the bursters in globular star clusters. These clusters are very simple, containing little gas or dust, so they may provide a good environment for study of the burster. If the burster were associated with a massive black hole, one might hope to find evidence of it by Space Telescope studies of the orbits of stars close to the hole, and perhaps very occasionally in tidal disruption of a star by the black hole. This latter process is thought to be rare but probably visible at great distance and might be discovered if one monitored the many globular clusters around massive galaxies.

Some important questions concerning neutron stars thus include the following:

1. What is the mass range of neutron stars both as they form and as they evolve by mass accretion in binary systems? Can neutron stars subsequently become black holes?

2. What is the maximum mass for a neutron star? How can such observations best be used to test equations of state of dense neutron matter, alternatively of Einstein's general relativity?

3. What can be learned observationally (primarily from time-variability) and theoretically about the internal structures of neutron stars and the properties of matter at extremely high densities? Can the likely presence of hadron superfluids be shown observationally to affect the dynamic response of a neutron star to the torque exerted on it by accreting matter? Do neutron

stars contain a core of condensed pions, solid neutrons, or even a quark liquid?

4. Are all neutron stars magnetic? Is the presence of the presumed magnetic-field-associated hard x-ray spectral feature in Her X-1 common to neutron stars, and if so what is the range of surface magnetic fields?

5. What are the magnetospheric properties and radiation mechanisms of pulsars? What are the properties of the Alfvén shell of matter found in rapid rotators such as Her X-1? How does matter enter the magnetosphere of a neutron star, and to what extent is it channeled as it moves toward the stellar surface? What are the properties of the matter column above the magnetic poles of neutron stars?

6. How is pulsed x-ray radiation produced?

7. Are pulsars primary sources of cosmic rays?

8. How can we detect dead pulsars? What is the mean density of neutron stars in the galaxy?

9. Can we find compelling evidence for black holes in binary or other stellar systems in our own and nearby galaxies?

Planets, Satellites, Asteroids, Comets

Many stars probably have, like the sun, a complex system of debris left over from their formation. Interesting astronomical problems lie in this area, some of them important to pending exploration and eventual utilization of our own solar system. In as far as studies of solar system objects can be conducted by astronomical instruments in space (as distinguished from space probes going to the objects), they might be regarded as falling under the cognizance of our Committee on Space Astronomy and Astrophysics. However, the SSB Committee on Planetary and Lunar Exploration (COMPLEX) has a more direct charge in this area and for several years has been considering such observations as part of its long-range study. Accordingly, we have not done an independent review of this area, but we direct attention especially to Section III.E of the 1978 COMPLEX Report (*Strategy for Exploration of the Inner Planets, 1977–1987,* National Academy of Sciences, Washington, D.C., 1978) as a reminder that several of the missions proposed in our report, including especially ST, Starlab, the Deep Ultraviolet Survey, and the Shuttle Infrared Telescope Facility, can and should be called on for critical solar-system observations.

GALAXIES

Introduction

The idea that the universe contains the large discrete aggregates of stars, gas, and dust that we call galaxies gained general acceptance only within the last generation or two. In 1914, Shapley showed that the sun lies toward the outer edge of the Milky Way system. Astronomers revived the old question as to whether many of the nebulous objects in the sky could be systems similar to our own galaxy. The problem was solved in 1925 when Hubble demonstrated that the Andromeda nebula was very distant and indeed similar in size to the Milky Way system. At about the same time, Hubble devised the familiar morphological system of classification of galaxies that now forms the basis for discussions of their evolution. In the 50 years since Hubble's work, several major developments have had a profound impact on the course of present work on normal galaxies. One was the realization that synthesis of the heavy elements takes place in successive generations of stars in the galaxies. Another was the notion introduced by Baade that the stellar populations of galaxies are of two distinct types, the metal-rich young stars (Population I) that comprise the disks of spiral galaxies and the metal-poor stars (Population II) that are found in elliptical galaxies and in the spherical halos of spiral galaxies. A successful attack on the problem of how galaxies evolve must thus combine a theory of their dynamical evolution together with a theory of their chemical evolution. The most commonly accepted picture is that elliptical galaxies and the halos of spirals were formed during an initial period of free fall. In any case, the rate of formation of new stars in ellipticals and halos is now considerably less than in the disks of spiral galaxies, where star formation has proceeded slowly over the lifetime of the galaxy (10 billion years). It is currently thought that the distinctions among the Hubble sequence of normal spirals lies in the rate at which they have used up their supply of gas, the early types (Sa's) having consumed most. The factors determining this sequence of spirals are not fully understood, nor is there a thoroughly satisfactory explanation of the spiral structure itself, although the density-wave model is beginning to shed light on this problem and has provided a general interpretation of the form and physics of spiral galaxies. Observations appear consistent with the idea that all normal galaxies were formed at about the same time, roughly 10^{10} years ago. Some recent observations of abnormally blue galaxies may be indicative of younger systems with ages as small as 10^8 years although the data are also consistent with the hypothesis that these abnormal systems are old objects that are currently experiencing bursts or flashes of star formation.

Clearly, the study of our own galaxy is of crucial importance. The sun is located some 10 kpc from the galactic center, almost exactly in the galactic plane. Because of the concentration of dust in the plane, our current knowledge of the overall structure of the galaxy is still relatively poor (for example, it is not possible to say with any certainty what kind of spiral we are in, normal or barred). However, penetrating views have been obtained through observations at several wavelengths: the high-resolution surveys of the 21-cm line of atomic hydrogen, the measurements of radio continuum emission believed to be synchrotron radiation from cosmic-ray electrons in galactic magnetic fields, the recent studies of CO emission lines, extensive local measurements of stellar motions, the spectral analysis of the chemical and physical state of the interstellar medium, and the gamma-ray observations of diffuse emission due both to cosmic-ray electron bremsstrahlung and to the interaction of cosmic-ray nucleons and interstellar matter. The synthesis of all these data is an exciting challenge, essential not only to an understanding of our own galaxy but also as a base for understanding the more violent processes observed to take place in other galaxies.

Since the identification of radio sources with the galaxies Cygnus-A and Centaurus-A by Baade and Minkowski in 1954, the study of galaxies has increasingly involved a class of phenomena, quite diverse in character, that may be loosely lumped under the heading "nonthermal activity." The "radio galaxies" such as Cygnus-A were the first recognized examples of such phenomena. Other examples include the abnormal jet coming from the center of the elliptical galaxy M87 and the wide emission lines in the spectrum of the Seyfert galaxy NCG1068 (which is the radio source 3C84). A common feature of the galaxies exhibiting nonthermal activity is that a vast amount of energy (sometimes exceeding the total luminosity of all the stars in the system) is produced in an astonishingly small nucleus that invariably lies at the center of the galaxy. In extreme cases, luminosities as high as 10^{46} ergs/sec may be produced in a volume less than a few light-days in diameter (as deduced from the rapid variability of some sources). A few of the nearer Seyfert nuclei are powerful x-ray sources with total x-ray emission comparable with that at optical wavelengths. The source of this energy is at present unknown, although most speculations concern gravitational collapse of some kind.

The quasars were discovered in the late 1950's as a result of optical identification of radio-source counterparts. Following Schmidt's spectroscopic study of 3C273 in 1963, it was recognized that these are the most distant, or at least the most highly red-shifted, objects known. Since then, a number of properties of quasars have been documented, largely through ground-based observations in the optical and radio regions. There has been some progress in infrared studies and x-ray detection (e.g., 3C273). The BL Lac objects appear similar to quasars in nearly all respects except that they display few, if any, conspicuous optical emission lines.

The emission-line red shifts of quasars extend from $z = 0.1$ to $z = 3.53$. If these red shifts are due to the expansion of the universe, the quasars offer a powerful probe of physical conditions in the early universe.

Quasars and active galaxies show very complex radio structure with evidence of compact components less than 0.001 arc sec across. The simplest interpretation of the data leads to the conclusion that these knots are expanding at speeds in excess of that of light in apparent violation of the principles of relativistic physics as we understand them. This is a clear indication of how limited is our understanding, and how much we may expect to learn through further study. Quasars usually appear starlike at optical wavelengths, although when the red shift is low they sometimes exhibit a faint surrounding nebulosity. In the only cases adequately studied so far the light from this nebulosity is primarily in line emission. The BL Lac objects are often embedded in nebulosity that in several cases comes from stars. The relationship between BL Lac objects and galaxies is thus well documented; the relationship between quasars and galaxies or BL Lac objects is, however, still uncertain. Studies of the magnitude and red-shift distribution have shown that the space density or luminosity of quasars (at least for the intrinsically brighter sources) strongly increases with red shift at least to $z = 2$.

It is commonly conjectured that the active galactic nuclei, in particular the Seyfert galaxies, are related to quasars. Indeed, Seyfert galaxies are known whose total luminosities, including that at infrared wavelengths, are comparable with those of the less powerful quasars.

In the past, galaxies have been treated as isolated systems. It has recently been recognized, however, that interactions, either with neighboring galaxies or with an external medium, may influence the evolutionary history. One indication of this possibility came about 10 years ago when the "high-velocity clouds" of neutral hydrogen were discovered at high galactic latitudes. These clouds have predominantly negative velocities and were interpreted by Oort as evidence for gas falling into the galaxy. Such an accretion process could have an important effect on the evolution of the galaxies. More recently, Mathewson and his associates have found evidence, also from 21-cm observations, of a "Magellanic Stream" of neutral hydrogen that appears to be associated with a close passage of the Magellanic Clouds and the galaxy. X-ray observations have shown that large clusters of galaxies often contain a very hot ($\sim 10^8$ K) tenuous gas that is evidently heated by the motions of the member galaxies. This gas is thought to have an important effect on the evolution of radio sources ejected from the galaxies themselves. Elliptical and S0 galaxies (those disk objects with no spiral arms and little detectable gas) dominate the central regions of these clusters; spiral galaxies are relatively much more abundant in the clusters' outer parts. It thus appears that S0 galaxies in clusters are produced when the gas is swept from spirals as they traverse the tenuous, hot intergalactic gas.

Normal Galaxies

Major efforts are still needed in documenting the contents of normal galaxies and the processes taking place therein. Only with such basic information can any worthwhile theoretical analysis be undertaken. The main requirements are to gain, for a reasonable sample of galaxies, an accurate picture of the following:

1. The mass distribution in galaxies;
2. The nature of the systematic and random velocity fields in galaxies;
3. The abundances of stars by composition, mass, age, and position in the galaxies;
4. The nature, state, and distribution of gas and dust in spirals and ellipticals;
5. The distribution of magnetic fields;
6. The energetic particle content;
7. The nature of the nuclei of galaxies;
8. The nature of the distribution of galaxies.

With such information it will be possible to investigate the more general problems of galactic structure and evolution, for example, the origin and maintenance of spiral structure, the reason for the low abundance of gas in ellipticals, the formation of the cool clouds from which stars condense, and the origin of cosmic rays. With improvement in the distance scale it will be possible to determine more accurately the size and masses of galaxies and clusters and perhaps to resolve the discrepancy between the masses thought to be needed to hold galaxies together and the masses thought to be needed to hold systems of galaxies together.

Stellar Distributions

Studies of the stellar content of our galaxy have concentrated on the solar neighborhood and the distribution of stars with distance from the galactic plane. These studies have led to mass estimates that exceed those for "visible" matter in the disk. Considerable effort is required to improve these data and hence improve our understanding of the mass distribution in the galaxy. The actual stellar content at distances exceeding 2–3 kpc from the plane of the galaxy is poorly known and could be substantially improved with high-sensitivity infrared spectroscopy. Virtually nothing is known concerning the stellar content of the outer regions of our galaxy or how our galaxy "ends."

The abundances of bright stars in the central parts of nearby ellipticals have been reasonably well documented, but improved angular resolution is required for observations of the nuclei ($<10^{-1}$ arc sec) and to study all types of galaxies at higher red shift for evolutionary effects. Space observations can provide this resolution along with substantial advantages in sky background suppression, especially in the red. Such studies will probably begin in the obscured regions of our galaxy, especially the galactic center. Populations of newly formed stars and horizontal branch stars can be studied, especially in the nuclei of galaxies, by observations in the ultraviolet. This will require spectroscopy at a resolution of $R > 10^3$ and a sensitivity of about 12 mag/(arc sec)^2.

The spatial extent of the stellar distribution also requires investigation both for isolated systems and galaxies in clusters where tidal effects may be important. Observations from space are advantageous in that the sky background in the near infrared is substantially reduced. Sensitivity to surface brightness better than 21 mag/(arc sec)^2 is required. The local population of high-velocity, low-luminosity stars can also provide data of this type for our own galaxy.

The Interstellar Medium

The existence of a general interstellar medium was not appreciated until about 50 years ago. Since then, we have recognized that the material between the stars is both the raw material and the product of stars and is a major determinant of galactic structure. The interstellar medium proves to have many components: atoms, molecules, solids (dust), magnetic fields, and cosmic rays. There is a very complicated and as yet only dimly perceived interplay between these components, the stars, and in some cases the galactic nuclei.

Much astronomical theory has been based on the hope that the detailed elemental abundances that can be determined in the solar system apply generally throughout the galaxy and beyond. It is important to test this hypothesis thoroughly, by observations of the interstellar medium in different regions of our galaxy and in other galaxies. How would major variations in composition affect cloud collapse and star formation? How would they influence the condensation of material onto dust grains or the formation of molecules?

The interstellar medium is the depository for the end products of stellar evolution. It is thought that virtually all the elements heavier than helium were produced in the interiors of stars and returned to space through mass ejection or violent explosions. Study of the interstellar medium therefore allows us to probe conditions in the interiors of stars and processes occurring during supernova explosions. It is generally believed that many of the cosmic rays are accelerated as a result of supernova explosions, but it is not understood how this acceleration occurs. Further study of detailed elemental and isotopic abundances in the cosmic rays will help us to understand the thermonuclear processing of material in stellar interiors.

The chemistry of the interstellar medium occurs under conditions that cannot be reproduced on earth. An understanding of the processes occurring in space promises to expand our view of the means by which atoms interact. For example, we do not know how complex molecules grow in interstellar clouds. What are conditions like on the surfaces of dust grains? How do atoms interact on these surfaces, and what materials do they produce?

The formation of life is thought to begin with the growth of complex molecules. The recent discovery in dense interstellar clouds of many molecular species of substantial complexity therefore poses fascinating questions about the origin of life. Could this process begin in the interstellar clouds? If so, how are the molecules tranferred to the surfaces of planets forming in these clouds?

The interstellar medium has a negative impact on some studies because of its opacity. Most of the central region of our galaxy, including its nucleus, is unobservable in the visible because of the intervening interstellar dust. A more complete understanding of the obscuring effects of the interstellar medium is essential for interpretation of observations of this and other obscured regions.

Over the past few years the picture of the interstellar medium has changed drastically. This altered picture is due to studies from *Copernicus* of the O VI ion in absorption and to studies of soft x-ray diffuse background radiation, both of which require interstellar gas in the temperature region 10^5-10^6 K. The volume of interstellar space occupied by this hot coronalike gas is large. Almost all stellar spectra searched for O VI show absorption features at 1032 and 1038 Å. The soft x-ray observations suggest that the sun is in one such hot gas region and that the general filling factor is of order 0.5. Questions that need an answer are the following:

1. What is the origin of this heated gas?
2. Is there pressure equilibrium, or are the x rays emitted from closely spaced shock fronts?
3. What are the temperature distribution and spatial extent of the hot regions?
4. How do clouds cool to allow collapse and the formation of stars?

The only available probes of the hot component of the interstellar medium are the O VI absorption lines and soft x-ray emission. Further, O VI data are needed as well as soft x-ray intensity studies with instruments capable of R = 20-100 spectral resolution and tens of arc minutes spatial resolution.

The dust and gas in interstellar space are the link between the dying and the newborn stars. Their composition and dynamics are keys toward understanding the metabolism of galaxies. To discover how elemental abundances vary within our galaxy and from galaxy to galaxy we need observations of interstellar absorption lines in more distant stars, such as those in other spiral arms, in the galactic halo, and in nearby external galaxies. Observations are also needed over very long pathlengths in very low-density regions (the "intercloud medium") for accurate measures of how the composition in our vicinity compares with that of the "normal" interstellar medium.

These investigations require an ultraviolet telescope and spectrometer capable of reaching stars at least as faint as 12th magnitude at resolution equal to or better than $R = 2 \times 10^4$, in order to study early-type stars in neighboring spiral arms and some hot white dwarf stars at high galactic latitudes. Measurements of interstellar gas constituents of low absolute abundance would benefit from, or require, considerably higher spectral resolution ($\sim 10^5$). On the other hand, measurements of H and H_2 can be made at $R = 10^3$, allowing much fainter stars to be reached with otherwise identical equipment. A capability of observing stars as faint as 18th magnitude at this resolution would allow measurements of H and H_2 in the spectra of early-type supergiant stars in the nearest external galaxies (early-type main-sequence stars in the Magellanic Clouds).

ELEMENTAL ABUNDANCES IN INTERSTELLAR SPACE

The first detection of a general interstellar gas was achieved as long ago as 1914 when interstellar Ca II absorption lines were found in stellar spectra. However, most of the important resonance lines from the interstellar gas (i.e., H, H_2, O, N, C, C^+, CO, and Si^+) fall in the ultraviolet wavelength range below 3000 Å, the shortwave limit of ground-based observations. Therefore, the number of species (and their contribution to the total number of atoms) detected in the interstellar gas by ground-based optical spectroscopy has been very limited. Measurements in the far ultraviolet, as with the spectrometer on OAO-3 (*Copernicus*), have vastly expanded our knowledge of the composition of the interstellar gas within a few hundred parsecs of the sun. The *Copernicus* results have also shown the special importance of observations in the 912–1150 Å range, which includes resonance lines of species such as H_2, D, Ar, N II, and O VI.

The *Copernicus* measurements, although the most detailed so far, are still limited to relatively bright and unreddened stars and hence sample only a very limited region of the interstellar medium in the immediate vicinity of the sun. Observations in the soft x-ray region may detect the absorption edges of interstellar material superimposed on the spectra of bright sources, providing a direct measure of elemental abundances independent of whether the material is in the form of free atoms or combined in molecules or in dust.

Interstellar gamma-ray lines are formed in the interactions of low-energy (MeV/nucleon) cosmic rays with constituents of the interstellar medium. One expects to find a sharp line component from de-excitation of interstellar grain nuclei, a relatively narrow line component from de-excitation of gas nuclei, and a broad line component from de-excitation of cosmic-ray nuclei. These three components can, in principle, be separated in spectra, permitting the study of both the interstellar medium and the cosmic rays. The strongest lines are expected to be at 4.44 MeV from the de-excitation of ^{12}C, at 6.13 MeV from ^{16}O, at 1.78 MeV from ^{28}Si, at 0.847 MeV from ^{56}Fe, and at 0.511 MeV from positron annihilation. Spectral features at 0.431 and 0.478 MeV could also result from the de-excitation of ^7Be and ^7Li. The first detector to be flown on a satellite to search for these lines will be on HEAO-C.

The sharp line emission by excited nuclei in grains offers an opportunity to determine the composition and spatial distribution of interstellar grains. The narrow line component also offers an opportunity for determining the spatial distribution and composition of interstellar gas because of the high transparency of even very dense interstellar clouds to gamma radiation and the lack of dependence of the gamma-ray emissivity on the chemical state, density, or temperature of the matter.

FORMATION OF MOLECULES AND DUST

Chemistry in space occurs in a mix of low and high effective temperatures, and possibilities for interactions between molecules must be rare because of their relative scarcity. These conditions are so different from those that we can study in chemical reactions in the laboratory that the discovery of complex molecules in interstellar clouds was quite unexpected by most astronomers. We now know of many such molecules but are only beginning to understand how they form.

Many molecular lines are detectable throughout the infrared and microwave spectral regions. However, problems of technology have limited our search efforts almost exclusively to the microwave region. Many important molecules such as H_2 and nonpolar molecules like CO_2 and CH_4 do not produce microwave lines. The resulting bias in our knowledge is a major obstacle to understanding how molecules form in space.

At submillimeter wavelengths, the detection of many new molecules and atoms in the interstellar gas is hindered by absorption and emission in the atmosphere and by the lack of sensitive detection techniques. The extension of detector technology from the microwave or infrared into this spectral region and the deployment of a large submillimeter-wave radio telescope in earth orbit are the tools needed for future more refined measurements of the composition of the interstellar gas clouds.

Infrared measurements of interstellar gas composition are also hampered by the earth's atmosphere, and the achievable sensitivity is limited because of thermal emission by the telescope optics, not by detector technology. A cryogenically cooled infrared telescope in space (aperture of at least 1 m) equipped with high-resolution spectrometers ($R = 10^4$-10^5) covering the 5-100 μm wavelength range is the instrument required for advancing this field.

Dust accounts for only 1 percent of the mass of the interstellar medium but is the most easily detected component. Obscuration at visible and ultraviolet wavelengths by dust grains frustrates astronomers who want to study objects that are more than a few hundred parsecs away in the disk of the galaxy. Although we study the centers of other galaxies in detail, the mere detection of the center of our own galaxy in the optical is made impossible by the intervening dust. Infrared observations of modest spectral resolution ($R = 10$)

but sensitivity 10–100 times greater than is currently possible are needed to improve the corrections that we now apply to obtain the intrinsic spectra of heavily obscured sources.

The formation and nature of the dust is itself an important problem. Although we do not know why materials condense efficiently on seed grains, and we can envision many mechanisms to destroy grains after they form, it is well established that nearly all the heavy elements in the interstellar medium are locked into dust grains. The chemical forms that these elements assume and the dependence of these forms on the environment in which the grains grow have been difficult to study because of the lack of spectroscopic features in the visible region. Recently, however, features have been observed in the ultraviolet and infrared at 0.22, 3.07, 10, and 20 μm and have been associated, respectively, with graphite, ice, and two bands in silicate absorption spectra. The strength of the first two features relative to the visual extinction and the general dependence of the visual extinction on wavelength show marked variations in different lines of sight. As a result, it is now becoming possible to test theories of the processes by which grains grow. Polarimetry is a further diagnostic tool for the properties of interstellar grains—in fact, it has already played an important role in establishing the dielectric nature of the grains. Studies of the polarization of starlight in the far ultraviolet and infrared due to interstellar dust, its wavelength dependence (e.g., at absorption features), and its dependence on extinction optical depth, would supplement available ground-based measurements to provide information regarding the shape, alignment mechanism, and composition of the grains.

These observations could be greatly extended by ultraviolet and infrared telescopes and spectrometers and polarimeters of spectral resolution $R = 30$ and capable of reaching stars of 12th magnitude (to study the interstellar dust out to neighboring spiral arms in our galaxy). Searches for other dust absorption features (e.g., the possible carbonate feature recently observed near 7 μm) should be pressed with these same instruments. Observations of a limited number of obscured stars at much higher spectral resolution are needed to search for clues to the specific chemical state of the material in the dust grains.

MAGNETIC FIELDS AND COSMIC RAYS

When considering the interstellar medium, one normally has in mind only the tenuous gas and the interstellar dust. Two other very important constituents account for about two thirds of the expansive pressure of the galaxy: cosmic rays and magnetic fields. It is now realized that the thermal gas in the galactic disk is only marginally capable of holding the cosmic-ray gas and magnetic fields against their dynamic pressures. Each of them contributes about 10^{-12} erg/cm^3 to the average energy density in interstellar space—an energy comparable with that of the turbulent motion of the interstellar gas. The existence of a galactic magnetic field causes a fundamental problem—where did this field come from? Could it have been "spun out" of the differential rotation of the galaxy? Or must we conclude that it is "permanent"? And if the latter, how could a magnetic field have been produced by the big bang?

The heating and ionization of the interstellar medium by low-energy cosmic-ray particles is an important unknown in understanding the state of the medium. The flux and energy spectrum of cosmic rays below 100 MeV/amu is still unknown. Indirect information, based on ultraviolet observations, has provided some arguments against ionization by cosmic rays, but these arguments have remained inconclusive. The determination of the low-energy cosmic-ray flux in the vicinity of the solar system outside the solar cavity is required and should be made.

The cosmic rays can also provide an excellent probe of average conditions in interstellar space. The method involves estimating the average confinement time of the cosmic-ray gas through the abundance of radioactive spallation products. For example, the isotope ^{10}Be (half-life 1.6×10^6 years) is found to be virtually absent, implying a confinement time well in excess of 10^7 years and hence a mean density of ambient particles substantially less than 0.1 atom cm^{-3} in the region of cosmic-ray confinement. Detailed experiments that lead to precision measurements of isotopic abundances in the cosmic rays (atomic number Z from 2 to 28, $\Delta A \leqslant 0.2$), and to the secondary-to-primary ratio at energies above 100 GeV/amu (Z from 2 to 28, $\Delta Z \leqslant 0.3$, exposure factor 10 to 100 m^2 sr day) are required to pursue these questions. An entirely independent piece of evidence will also reveal the confinement time: the shape of the electron spectrum and, in particular, the shape of the positron spectrum up to a few hundred GeV. The technology for this experiment is available, and a measurement of positron spectrum from 10 to 200 GeV (exposure factor ~1 m^2 sr day) should be made.

The distribution of cosmic rays throughout the galaxy is revealed by high-energy gamma rays resulting from the interaction of cosmic rays with the interstellar matter. Recent results indicate that the cosmic-ray density is enhanced in the spiral arms. Future gamma-ray observations are expected to provide a high-contrast view of galactic features.

Masses of Galaxies

Basic to the study of galaxies is the total galaxy mass and how the mass is distributed. A substantial amount of information is available from ground-based studies of velocities of gas and stars in galaxies and of galaxies within clusters. This has led to the problem that the mass that we think is needed to hold a cluster together often is a factor of 10 or so larger than the mass deduced from the visible portions of the galaxies. Both sides of this problem need further work.

Studies of the structure and dynamics of groups and clusters of galaxies still are somewhat schematic. More systematic approaches will require a considerable amount of observational work (red-shift measurements, search for atomic hydrogen bridges and stellar bridges between galaxies) and theoretical work. On the other side of the problem, we have only meager knowledge of the mass distributions within elliptical and S0 galaxies. The observational problem is that these galaxies have low surface brightness and weak or nonexistent emission lines. Thus, most measured velocity dispersions for elliptical galaxies refer only to the nuclear region. Of pressing importance is the problem of extending these measurements to regions well outside the nucleus. For both elliptical and spiral galaxies there is considerable interest in discovering how far out the halos extend and what sorts of stars or other objects might be present in these halos. Space observation, particularly in determining masses in nuclei (resolution better than 10^{-1} arc sec) and in measuring low surface brightness [fainter than 25th magnitude (arc sec)$^{-2}$], can play a key role.

Nuclei of Galaxies

Some galaxies show evidence of violent disruptions that seem clearly associated with activity in the nucleus. This has attracted considerable interest as a problem in its own right and for its possible relation to the still more violent events in quasars. But "normal" large galaxies also have nuclei, and a close study of these less complicated objects is essential to any understanding of active galaxies. Indeed, the nucleus of our galaxy has an importance in this area similar to that of the sun in stellar studies, and for the same reason—its proximity permits observation on a level of completeness and detail that is totally inaccessible for any other similar object.

Among the questions to be answered by study of normal galactic nuclei are the following:

1. What types of objects populate these regions? For example, do active sources in a quiescent state lie at the centers of galaxies not now considered to be active?
2. What causes large-scale motions of matter in and out of galactic nuclei?
3. What are the elemental abundances in galactic nuclei, and how do these abundances reflect the history of these regions?
4. How is the rate of star formation affected by conditions not typical of the general interstellar medium, such as abnormal abundances, high mass density, and differences in gas dynamics?
5. What is the relationship between characteristics of the galaxy as a whole and characteristics of its nucleus?
6. What is the evolutionary sequence of galactic nuclei—do all galaxies go through "active" stages, with powerful nonthermal nuclear sources?

Studies of our own galactic nucleus must emphasize the radio, infrared, x-ray, and gamma-ray spectral regions because of strong interstellar extinction that makes optical and ultraviolet work impossible. A first step is to conduct detailed surveys of this region at high sensitivity and the highest possible angular resolution to achieve a complete picture of the sources to be found. Work in the radio region has been particularly hampered by the difficulty in making high-resolution maps of such a southerly source with existing installations. In the infrared, a large (2-3 m class) telescope in space would yield improved angular resolution, but eventually interferometric observations will be needed to achieve the highest possible resolution. Detailed x-ray and gamma-ray observations are needed at high angular and temporal resolution (a relatively large number of x-ray bursters are already known to lie toward the galactic center).

Sensitive near-infrared spectrometers would permit identification of the types of stars near the galactic center and provide evidence for abundance anomalies. The interstellar medium in this region needs to be studied through radio and infrared spectroscopy and through gamma-ray measurements, as described in the preceding discussion of the general interstellar medium.

The nuclei of external galaxies have a particular significance for evolutionary studies, which will require a thorough understanding of a large number of objects. As an example, the nucleus of M32, a companion of the Andromeda nebula, is interesting because it appears to be so simple—a cusplike peak in the light distribution. Is this a purely stellar nucleus? What lower bound can we place on the density of stars at the center? What bound can we place on the mass of a possible compact object in this nucleus? The key instruments in space needed to reveal the dynamics, abundances, and properties of the stars and the interstellar medium in these regions appear to be a 2-3 m class telescope at 0.1-arc sec resolution for the optical and ultraviolet and a 1-2 m class cooled telescope for the infrared.

Active Galaxies and Quasars

Among the more important questions concerning active galaxies and quasars are these:

1. What is the origin of the energy emitted?
2. What processes are responsible for the radiation in the different wavelength bands, and what are the reasons for the apparent correlation between the spectral index and continuum polarization?
3. Why is there such wide variation in observed properties of active galactic nuclei—does it indicate fundamental differences in, say, primary energy source?
4. What is the nature of the interaction of the active event with the surrounding gas and stars?

5. What is the origin of the absorption lines observed at high relative blue shift in the spectra of many quasars and some galaxies?

6. What is the chemical composition of quasar material and the origin of heavier elements in the quasar?

7. What is the number density and evolution of these sources with cosmological epoch? Why do only about 2 percent of giant galaxies show active nuclei?

8. What relation exists between quasars, active galaxies, and normal galaxies?

While answers to some of these questions will eventually be obtained from ground-based observations, there are many important problems that will only yield to study from above the earth's atmosphere. This is due mainly to the need to observe in the regions of the spectrum where the atmosphere is either opaque or too bright. There is also a requirement in the visible to resolve faint structures on an angular scale very much less than 1 arc sec and to analyze them spectroscopically; this cannot be accomplished from the ground.

In order to understand the energy production and radiation mechanisms, it is essential to know the form of the emitted continuum and the degree of variability and polarization as a function of wavelength. While the radio, near-infrared, and optical emissions are documented reasonably well, there is evidence that active galaxies and quasars may emit most of their energy in the far infrared. Studies have so far been limited to only a few selected cases at wavelengths >20 μm. Immense progress could be made if a high-sensitivity general survey were available with well-defined passbands in the 5-μm to 1-mm region. Studies of individual sources to determine infrared energy distribution and variability are also essential. The ultraviolet region is of interest because it determines the ionization structure in the surrounding gas and, hence, the emission line characteristics. The region between 200 and 912 Å in the rest frame is especially important in this context as it contains the H I, He I, and the He II ionization edges. The optimum approach in this spectral region is spectrophotometric observations of individual sources; this requires a telescope of moderate to large aperture and sufficient spectral resolution to measure the absorption edges ($R = 30$). X-ray and gamma-ray observations of active galaxies and quasars are also crucial in that they provide information on particle energies, magnetic-field strengths, and photon densities in the emitting regions; x-ray data are important for ionization studies as well. Even good upper limits are valuable in this context as they could rule out several classes of radiation mechanism. Again, sensitive survey work would be very useful, provided positional accuracy is adequate for identification with known optical or radio sources.

Because of the high radio brightness temperature of most quasars and BL Lac objects, it is unlikely that emission-line studies at radio wavelengths will be profitable. Absorption lines, especially that due to the 21-cm hydrogen line are, however, extremely valuable as probes of conditions in the absorbing gas. When combined with L-α column densities, the 21-cm line results will permit direct determination of the spin temperature in the gas. In the far-infrared region, investigations will be mainly exploratory in nature and positive results will depend on the extent of the surrounding emission zone and the role of dust.

Extending spectroscopic observations into the ultraviolet and infrared is of crucial importance in the study of quasars. At present, comparison of objects of widely differing red shift depends on totally different spectral lines, since those observed in one of the objects are red shifted out of the optical region or not red shifted into it in the other object. Thus, the number density of absorption lines in low red-shift objects is currently unknown but could determine how much of the absorption seen in higher red-shift objects is intrinsic to the object and how much is due to clouds at lower cosmological red shift. A similar problem arises in the study of the emission lines because it is currently not possible to observe the key forbidden and resonance lines in the same object. If significant evolution occurs, it could not at present be detected and would lead to erroneous interpretation of the emission line data. Space observations of moderate resolution ($R = 10^3$) would solve both problems.

As both intrinsically fainter and more distant quasars are located, it may be possible to determine whether heavier elements are indeed processed in these objects. For example, the metal content may systematically vary with luminosity or red shift. In principle, emission- or absorption-line data can be used, with perhaps a preference for the latter if sufficiently high resolution can be obtained, since their interpretation is less model dependent. Sky background and detector noise are serious limitations for ground-based observations because of atmospheric seeing. Both problems can be reduced substantially (~5 mag) for space observations. Spectroscopic observations of 25th-magnitude objects should be possible without encountering severe background problems and should result in a wealth of data on lower luminosity and higher red-shift quasars—essential if we are to understand the evolution of these objects. In order to keep observing times short, however, a large telescope is required.

To study conditions close to the primary source, we need similar spectroscopic observations both of active galaxies and of quasars. Studies of ultraviolet resonance-line emission are required to test models of ionization structure and to obtain abundances. Investigations of resonance absorption lines (strengths and velocities) are needed to provide information on the dynamics of ejected material, and observations of infrared lines (fine structure or molecular transitions) may measure cooling in sources not dominated by high brightness temperature continua. The required instrumental capabilities are similar to those already described.

It is difficult to project the number of active galaxies and quasars that may be detected as x-ray or gamma-ray sources, but there are grounds for optimism. It may then be possible to search for x-ray spectral features to determine the role of any hot gas in these objects.

Understanding of both the continuum and line formation regions in active galaxies and quasars requires analysis of the geometry of these sources not only on the finest angular scale possible but also as a function of the wavelength of observation. We need optical and UV studies or morphology and spectrum with angular resolution better than 0.1 arc sec, and this is best achieved through a filled-aperture space telescope of size exceeding 2-3 m. Of pressing interest is the nebulosity around quasars and BL Lac objects and the further search for possible stellar absorption lines in this nebulosity. The radio results achieved through very-long-baseline-interferometry measurements give evidence of structure on scales of milli-arc seconds, and this structure is time variable. Interpretation is difficult, however, because the "aperture" is poorly covered. One important step would be the use of an orbiting telescope to fill in the Fourier-transform plane. The x-ray observations of nuclei together with the radio data may yield important information on radiation mechanisms, and x-ray observations of the jet in M87 would be of great importance to our understanding of magnetic and particle structure in these sources. Angular resolution of several arc seconds would be adequate initially but very low surface brightness may be a problem.

Any attempt to resolve the "emission-line region" would require resolution better than a milli-arc second. Such resolution could only be achieved interferometrically but would yield important information on source geometry as well as clearcut tests of quasar–active galaxy models.

Most quasars have been identified by locating objects with ultraviolet excesses at the approximate positions of radio sources. This procedure provides a biased sample for studies of evolution or of objects at large red shift. For example, where very accurate radio positions have been used, quasars with neutral or red continua have sometimes been found. At large red shifts ($z > 3$), even objects with blue nonthermal continua may appear red if they are subject to strong Lyman absorption, as is the situation in a number of already known objects. It is therefore important to extend quasar search techniques. One possibility is work into the near infrared, which for faint objects will require operation in space to avoid atmospheric emission.

High angular resolution should also permit a significant increase in the number of detectable quasars. Observations from space should permit detection of quasar candidates to 27th to 28th magnitude and crude spectroscopic analysis to 25th magnitude given a large (>2 m) aperture telescope. This, in turn, will allow for more reliable estimates of the luminosity function of quasars as a function of epoch and in particular a better understanding of the suggested "cutoff" beyond $z = 2$. It is, in principle, possible that quasars with red shifts much in excess of 3.5 may be found in this way.

Interaction between Galaxies and the Ambient Medium

The main questions in regard to interaction between galaxies and the ambient medium are the following:

1. What is the origin of the intergalactic material in clusters, and what are its physical characteristics?
2. How does the presence of this material affect the dynamical and physical evolution of individual galaxies?
3. What is the relation between this material and the properties of the radio sources observed in clusters?
4. What is the origin of the neutral clouds entering our own galaxy, and how can this be related to mass ejection from interacting galaxies?

A discussion of the intergalactic medium and its relationship to galaxies is given in the next section. The space-research effort will be directed toward x-ray observations, especially imaging (1-10 arc sec resolution) of clusters to determine the structure in the cluster gas and, from the continuum energy distribution, the corresponding temperatures and densities. Emission-line spectroscopy ($R = 10^2$) is also a potentially powerful tool in this regard. These studies, especially if combined with analyses of radio-source structure, optical structure, recombination line emission, ultraviolet absorption, and emission-line spectroscopy, should provide a dramatic breakthrough in understanding the interaction of galaxies with an ambient medium.

COSMOLOGY

Introduction

To understand the status and prospects for cosmology it is useful to recall the history of its development. This can be put in three phases.

Discovery (1925-1935): Hubble showed that the "spiral nebulae" are galaxies of stars like the Milky Way, that these galaxies are nearly uniformly distributed through space, and that their spectra tend to be shifted toward the red in direct proportion to their distances. Friedmann and Lemaître showed that these phenomena are consistent with a uniformly expanding general relativity world model. It was realized that these models are characterized by a few (albeit difficult to determine) cosmological parameters: Hubble's constant, H_0, which measures the present rate of expansion; the acceleration parameter, q_0, which measures the rate of change of H; the time, t, since the big bang (assuming there was one); the mean mass density, ρ, and pressure, p; the cosmological constant, Λ; the radius of curvature of space, R; and the sign of the curvature which indicates whether the universe is open or closed. General relativity gives three relations among these parameters. Tests for the parameters were devised. If the tests could be accomplished and the results were found to be consistent with these relations, it would be an important test of general relativity theory and of the world models, and it would bring us closer to answering the questions of how the universe begins (big bang, quasi-static Einstein model, . . .) and how it ends (expansion forever, collapse back to a singularity, . . .).

Re-evaluation (1935-1960): These rapid developments were followed by a period of discussion and reassessment. The evidence for the linear distance-red shift relation was substantially improved and the distance scale appreciably revised. A wealth of data on the nature of the galaxy distribution was painstakingly accumulated. On the theoretical side, people asked whether general relativity theory really is needed or wanted (Milne), whether the universe if expanding really is evolving (Bondi, Gold, and Hoyle), and for that matter whether the universe really is expanding.

Application of new technology (1960-present): One general example will illustrate the impact on the subject by the introduction of new technology—new problems and new ways of looking at old problems. Radio astronomy has led to topics as diverse as probes for extragalactic atomic hydrogen, the debate on the nature of the quasi-stellar radio sources, the puzzle of apparent superrelativistic velocities in some radio sources, and the discovery of the microwave background (consistent with being a residuum of the big bang).

Predictions of future research are uncertain, and particularly so here because the observational base is so small that any new development can have a profound effect on general opinion and on the direction of research. However, it seems reasonable to guess that there will be continuing interest in the cosmological parameters (a problem posed in the 1930's!), in the nature of structures like galaxies and clusters of galaxies and what they are telling us about physical processes in the universe, and in the search for a coherent theoretical scheme of evolution that can tie physical processes operating "from the beginning" to all the phenomena that we can muster—the nature of galaxies and their contents, the motions and distributions of galaxies, the radiation backgrounds. The following are some ways in which space science may be expected to affect this venture.

The Distance Scale

Relative distances of galaxies can be measured with fairly good reliability by comparing relative apparent brightness. Absolute distances are much more uncertain because they require absolute galaxy luminosities, and these are only estimated in a highly indirect way. Knowledge of the distance scale is essential for computation of processes like attenuation of extragalactic cosmic rays and production of x rays by intergalactic plasma. In the relativistic models, the distance scale fixes the time scale, and this is needed for comparison with chronologies deduced from the radioactive elements or from stellar evolution.

Cepheid variable stars have been measured at distances approaching one fifth the distance to the Virgo cluster of galaxies. It would be of considerable interest to increase this limit because there is evidence for appreciable systematic peculiar motions of the galaxies on scales comparable to the distance to the Virgo cluster. This is a very difficult task, but it may be made possible by observations from above the atmosphere. If the angular resolution were increased by a factor of 10, to 0.1 arc sec, it would reduce the flux of light from stars around the wanted variable star by a factor of 100, more than making up for the loss of collecting area in going to a space telescope.

Nature of the Distribution and Motions of Galaxies

The most direct evidence for the general expansion of the universe is the Hubble diagram—the galaxy apparent magnitude as a function of red shift, z. The data for giant elliptical galaxies are consistent with Hubble's law, z proportional to distance, to about 20 percent accuracy at $z = 0.1$. However, departures from Hubble's law at low z must show up at some level because of peculiar motions, and other departures may show up because of local mass concentrations or failure of the assumed large-scale symmetry of the universe. One way to get at this may be to replace apparent magnitude with distance indicators more precise and applicable to a broader range of galaxies. (The apparent magnitude is useful only to the degree that one can select a uniform class of galaxies—"standard candles.") If one could observe galaxies with a factor of 10 better angular resolution and adequate surface brightness sensitivity to reveal features, one should have an improvement in luminosity classification (in which one attempts to place galaxies in classes of intrinsic luminosity by their visual appearance). This, along with measurements of individual bright stars and H II regions, both thought to be useful "standard candles," and of supernovae would permit a greatly improved picture of the distribution and motion of the galaxies out to the distances of the nearer clusters of galaxies. This is of interest because the galaxy distributions and motions test our theories concerning time variation of galaxy distribution in an expanding universe.

All the above discussion assumes that the observed galaxy red shift measures the rate of change of the distance to the galaxy. A direct test of this assumption is possible, for it implies that the surface brightness of a galaxy (with standard intrinsic surface brightness) varies with red shift z as $(1 + z)^{-4}$. Ground-based tests for this effect are limited by the fact that galaxies at $z > 0.1$ are barely resolved–the run of surface brightness across the galaxy is strongly affected by seeing. Improvement by a factor of 10 in angular resolution with adequate surface brightness sensitivity would yield a considerable advancement in this test.

Mean Mass Density

The mean mass density, ρ, is important because it tells how gravity should be affecting the rate of change of the expansion rate (and, if $\Lambda = 0$, this tells whether the expansion will eventually stop and the universe collapse again). It is also essential to attempt to piece together the evolution of large-scale systems like clusters and superclusters of galaxies. The types of matter making appreciable contributions to ρ are of fundamental interest as clues to the history of the universe. We cannot hope to measure all possible contributions to ρ, but we can hope to make useful progress by systematically assessing all possible lines of evidence.

THE EXTRAGALACTIC LIGHT

We know that the extragalactic contribution to the background radiation at optical wavelengths ought to be based on standard galaxy luminosities and number densities and on the Friedmann-Lemaître cosmological model. A discrepancy would indicate either that we have missed an important contribution or that one of these numbers is wrong. It is easy to imagine that we have missed substantial numbers of objects too compact to be distinguished from stars or with surface brightness too faint to be detected against the light of the night sky. Since ground-based observations of the background at 5000 Å are limited by airglow, measurements must be repeated above the atmosphere. The background in the near-infrared (1 μm) is of particular interest because galaxies are bright there and galaxies at great distance might be making an appreciable contribution. Here ground-based observations have not been possible because the airglow is too intense, so observation from space is required.

THE SEARCH FOR AN INTERGALACTIC MEDIUM

If there were an appreciable mass density in an intergalactic plasma, the recombination radiation would make a step in the ultraviolet background at

L-α. The measurement, of course, has to be done above atmosphere, and it would require considerable care because one is looking for a change in level across the strong local L-α line. It has also been suggested that helium lines from an intergalactic plasma at moderate red shift could produce features in the ultraviolet spectrum. In addition, the ultraviolet spectrum of extragalactic objects, shortward of L-α, is a powerful probe for atomic (or molecular) hydrogen clouds along the line of sight. (The alternative–21-cm absorption–is less sensitive and the interpretation more difficult because it depends on the hyperfine-spin temperature.) Many theorists argue that there must be debris of some sort, such as the above-mentioned clouds, left over from the formation of the galaxies. If we could detect and identify the debris, it would be a powerful stimulus to a believable theory of the origin of the galaxies.

Of continuing interest is the question of whether an appreciable part of the x-ray background could be contributed by an extragalactic plasma. Moderate- to high-angular-resolution studies will be essential to test whether there is a true "diffuse" component, whether there might be a contribution from a filamentary or patchy intergalactic medium, and whether the x-ray flux correlates with the very large-scale clumps of matter revealed in the galaxy distribution.

THE PROBLEM OF MATTER AND ANTIMATTER

Laboratory experiments show rather precise symmetry of matter and antimatter. It would thus be plausible for the universe to show the same symmetry. Two current lines of research might eventually shed some light on this question. First, there is reason to suspect that at least some cosmic rays, the extremely high-energy (10^{20} eV) events, are extragalactic because the expected curvature in the galactic magnetic field is small and the directions of incidence are close to isotropic. At the other end of the scale, it is now known that the abundance of antimatter in the $<10^{11}$ eV cosmic-ray nuclei is small. Thus, if one understood well enough the physics of cosmic rays, it should be possible to establish what fraction of these nuclei might be extragalactic and what fraction of the nuclei might be antimatter. On the other side, the positive detection of even one antimatter atomic nucleus of high atomic number would be strong evidence for at least pockets of antimatter. Second, gamma rays from matter-antimatter annihilation might point to regions where matter and antimatter are coming into contact.

The Origin of Galaxies and Clusters of Galaxies

NATURE OF THE DISTRIBUTION OF STARS IN THE EARLY UNIVERSE

There is increasing interest in attempting to understand what the observed clumping of matter–in galaxies and clusters of galaxies–might be telling us about the history of the universe. When did galaxies form? What did they look like as they were forming? Which came first, galaxies or protoclusters of galaxies? An invaluable guide to speculation would be some knowledge of what the sky "looks like" at a red shift of 3, or 10, or 30. Do the galaxies light up as hard bright spots? Or as diffuse or filamentary patches? Or is there no well-defined turn-on point? To help find out, deep scans are needed of the background at high angular resolution and to very low surface brightness. Since it is not known when galaxies formed, we should have data from a broad range of wavelengths–infrared, optical, and ultraviolet. Ground-based observations at visible wavelengths have not yet been exhaustively attempted. The crucial measurements in the infrared (and ultraviolet) await observations from above the atmosphere.

EVOLUTION OF GALAXIES–ABSOLUTE INFRARED FLUX MEASUREMENTS

Absolute measurement of the infrared background may provide useful constraints on models for galaxy evolution. It is commonly assumed that the elements heavier than helium have been produced in stars and that the energy produced in making the observed elements plus whatever is locked up in star remnants was released in the form of electromagnetic radiation at ~1 eV. The radiation should still be present, although red shifted by an amount determined by the epoch at which it was produced. The limits we now have on the absolute infrared background intensity, 1 μm to 1 mm, do not provide very strong constraints on the more popular scenarios for galaxy evolution. Substantial improvements in the measurements would be difficult but, it appears, technically possible, and would be of considerable use as tests of the models.

THE EVOLUTION OF CLUSTERS OF GALAXIES

An interesting guide to the evolution of large-scale structure in the universe may be provided by the x-ray observations of clusters of galaxies. These cluster x rays seem to be produced by hot intracluster gas, and it has been suggested that this gas may have been accreted after the cluster formed. If so, it would be an interesting indication of the existence, amount, and distribution of diffuse extracluster matter. Another possibility is that the gas has been shed by the stars in the cluster galaxies. Thus, the amount of gas is a useful measure or upper limit on the amount of stellar evolution subsequent to the formation of the cluster. Of considerable interest is the measurement of x-ray emission lines from heavy elements, to be expected from matter shed by stars. Also, one is interested in shocks or plumes of emission reaching from the central parts of the cluster, as may be expected if gaseous matter were falling in. Since one would hardly expect that the gas would fall in a spherically symmetric way, one would expect that, as long as the mass is accumulating at an appreciable rate, the x-ray luminosity distribution would tend to show departures from spherical symmetry about the cluster center. Depending on the initial matter distribution around the cluster, such anisotropies might be more important at red shifts $z > 1$ than they are now and may be most important when the cluster is forming, perhaps at $z = 1$ to 3. Thus, it will be of considerable interest to see the results of extending the x-ray observations of clusters to red shifts on the order of unity. As a related application, it has been pointed out that x-ray detection of clusters at $z = 1$ will provide useful markers for optical study of high-red-shift galaxies.

Galaxies at High Red Shift

By 1930, Hubble had fairly good evidence that galaxies are uniformly distributed and uniformly moving apart from each other in the large-scale average. An essential next step was to push these observations to galaxies at greater distance. In a massive effort, Hubble and Humason mapped out the mean galaxy distribution to $z = 0.2$. The data were not accurate enough for the main goal, a direct test of the relativistic expanding world model, but they did establish that at such great distances there are galaxies much like the nearby ones and in abundance comparable with the local density of galaxies.

With the great development in technology since 1930 we should be able to push the exploration much further out, to get at least some data on galaxies at red shifts of unity and beyond. As the light travel time from an object at $z = 1$ is about 50 percent of the presumed age of the universe, this would be an exploration back in time as well as out in space. What does a galaxy at $z > 1$ look like? Is there evidence for evolution in luminosity or increased activity in nuclei? Can we pick out any relation to the properties of quasars? Can we see any evidence that galaxies and/or quasars are in the process of forming? Are these galaxies at $z = 1$ more strongly clustered than are the nearby galaxies, as would be expected if galaxies formed in protoclusters, or are they less clustered, indicating the clusters formed after the galaxies?

Very deep surveys are needed, in sample areas, of galaxy angular position, apparent magnitudes, broadband colors, and angular diameters well past the present magnitude limits (~22nd magnitude). Since the red shift is displacing the galaxy light to the red, it is desirable to have high sensitivity and angular resolution in the near infrared. Since the distant galaxies are diffuse objects, just resolved at 1 arc sec, space observations made above the airglow are particularly valuable. Since an appreciable fraction of the light from a distant galaxy is in a nucleus unresolved at 1 arc sec, improved angular resolution also improves the depth of the survey.

Microwave Background

SPECTRUM MEASUREMENTS

The first goal is to check that the spectrum of the microwave background does approximate a Planck spectrum, as expected if this is the primeval fireball radiation left over from the big bang. Assuming that this is so, the detection of any departures from a pure Planck spectrum (apart from the local contribution from the galaxy) would be an important clue to the history of the universe, such as the details of the interaction of matter and radiation and the mixing of radiation from different parts of the universe at different "initial" temperatures. Ground-based observations have mapped out the spectrum in fair detail to about the peak of the Planck curve at several millimeters wavelength. The first good evidence that the spectrum does drop down again as it should shortward of this peak has been obtained in a recent balloonborne measurement. Radiation from the atmosphere above the balloon, however, was a serious limitation. In view of the fundamental signficance of the primeval fireball hypothesis, more detailed absolute flux measurements above the atmosphere are of pressing importance.

ISOTROPY MEASUREMENTS

Anisotropy in the intensity of the microwave background would be caused by our peculiar motion relative to the large-scale matter distribution, by initial irregularities in the distributions of matter and radiation, and by absorbing and radiating objects along the line of sight. The first effect is of particularly immediate interest because it is closely tied to studies of the systematic deviations from Hubble flow (uniform isotropic expansion) in our "neighborhood" (in and around the Virgo cluster of galaxies). This in turn is fundamental to our understanding of the evolution of density irregularities: How does the concentration of matter around the Virgo cluster affect the motion of the matter? We already have some idea of the peculiar velocity field from studies of the systematics of galaxy red shifts and distances, and as more of these data are accumulated in a systematic way we should have an increasingly good measure of it. We are fortunate that the microwave background can provide a benchmark—our velocity relative to very distant matter.

Our peculiar velocity causes a cos θ type anisotropy in the microwave background intensity, with amplitude proportional to the velocity. Present measurements give a solar velocity (or perhaps an upper limit) of about 350 km/sec. The accuracy is limited by the galaxy (which contributed a cos θ component that we can only imperfectly subtract out) and by the atmosphere (which contributes noise and, depending on location, a spurious signal correlated with large-scale geographic features). The effect of the galaxy is reduced by observing at shorter wavelengths, but this increases difficulties with the atmosphere. Observations from the ground, from balloons, and from high-altitude aircraft all hold promise for significant further results, but it seems likely that the best attack on this problem will be through measurements made above the atmospheric emission.

Primeval Element Abundances

In the standard (simplest case) big bang cosmological model, there is the remarkable prediction that before the first stars form about 75 percent of the matter is hydrogen, most of the rest helium-4, with traces of deuterium, helium-3, and lithium-7. The predicted helium-4 abundance is quite insensitive to the parameters of the standard cosmological models. It assumes that there was a big bang, that it can be described by the laws of physics as now understood, and that the nuclear reaction rates were not influenced by high neutrino number (the electron or muon-type neutrino number density taken to be very much less than the photon number density). The predicted deuterium and lithium abundances also depend on the present mean mass density, ρ.

It is a further remarkable coincidence that the predicted and observed helium abundances agree, and with a not unreasonable choice for ρ the same is true for the deuterium abundance. The observed helium abundance is nearly the same in a wide range of objects, consistent with the idea that the helium was formed in a universal process before stars produced the heavier elements. To extend the test, one would like to have the helium abundance in a still broader range of objects, particularly those with extreme deficiency of heavier elements: excellent candidates are H II regions in dwarf irregular galaxies.

The best estimate of the deuterium abundance is thought to be the one based on the ultraviolet resonance absorption line measurements by the *Copernicus* satellite. The problem is that this samples only a few relatively nearby stars, and the results indicate possible variations in abundance. One would very much like to compare these "local" samples with the deuterium abundance in the gas in the Magellanic Clouds, for example, where physical conditions and (in the Small Magellanic Cloud) heavy-element abundances are different from those in our galaxy.

Space Curvature and Deceleration—Tests of the Relativistic World Model

Many of the subjects discussed above are not very specific tests of the standard relativistic world model. For example, Hubble's law follows directly from the assumed large-scale symmetry and expansion of the universe. Primeval element abundances are very specific tests but depend on such an enormous extrapolation back in time that they must be treated with considerable caution. The straightforward test is to measure a number of cosmological parameters and see whether they agree with the relations predicted in general relativity theory. This project has been pursued since the 1930's. There has been considerable progress in understanding the problems and how to deal with them, but so far we have only highly tentative answers. Interesting tests include the following:

1. Red-shift-magnitude relation. The variation in the relation from low to high red shift measures combined effects of space curvature and deceleration of the expansion rate. A major difficulty is time evolution of the intrinsic galaxy luminosity.
2. Red-shift angular size effect. Under general relativity theory this measures the same thing as the first test but since the observational problems (systematic measuring error, evolution correction) are very different, both tests are needed. People have considered using angular sizes of a variety of objects. For radio sources, a problem is that the physical size seems to depend on the (evolving) ambient gas density. For clusters of galaxies it is not yet clear that one can find a precise enough measure of some characteristic length such as a core radius. For angular sizes of galaxies at large z, the present limitation is that the image spreading by the atmosphere is comparable to the size of the object. A considerable improvement of the test will follow from space observations, giving better angular resolution coupled with ability to detect low surface brightness.
3. Galaxy count versus magnitude (or galaxy count versus red shift) relation. This measures the same thing as the previous tests under general relativity theory with the assumption that the cosmological constant Λ vanishes.
4. Chronology. The age of the universe since the big bang is fixed by the distance scale together with the dimensionless cosmological parameters. This is to be compared with the radioactive decay ages of the elements and stellar evolution ages. The results are in fairly close agreement but not yet within the accuracy needed for a strong test. Improving the ages of stars and of elements will require developments across a broad front. For example, there is the theoretical and observational problem of piecing together the sequence of evolution of abundances of the elements in the galaxy.
5. Mean mass density. This is an important parameter in the theoretical relations among the cosmological parameters.

The systematic attack on these very difficult problems is likely to continue for many decades. To the extent that the results from different tests are consistent with each other, we will have reason to be confident that they are telling us what the geometry of the universe is like and how the expansion will proceed.

Summary

A number of observational programs could be commenced in the next few years that would have an important effect on the direction of research in cosmology. We list here some of the main areas in which observations from space may be expected to play an important role.

1. Primeval fireball radiation.

(a) Absolute flux measurements capable of reaching a 3 K Planck spectrum at 1 cm $> \lambda >$ 0.05 cm.

(b) Isotropy measurement capable of detecting antenna temperature variations $\delta T/T = 3 \times 10^{-4}$ on angular scales $\theta > 10^\circ$ and wavelengths in the range 1 cm $> \lambda >$ 1 mm.

2. Absolute background measurements, ultraviolet through infrared.

(a) Ultraviolet flux measured to accuracy better than 3×10^{-6} erg cm^{-2} sec^{-1} sr^{-1} just longward of 1215 Å to test for local recombination radiation from intergalactic plasma or emission from an intergalactic plasma at high z.

(b) Infrared flux measurements to $< 10^{-3}$ erg cm^{-2} sec^{-1} sr^{-1} (100 μm $< \lambda <$ 1 μm) to test for integrated emission from all generations of stars, galaxies, protogalaxies, and protoclusters at $z < 10^3$.

3. Extragalactic infrared sources. The goal here is to discover the "appearance" of the sky due to the light from young and perhaps quite luminous galaxies. Suggested angular sizes of young galaxies range from a few tens of arc seconds down to well below 1 arc sec, depending mainly on how compact young galaxies were when they first "turned on." One might also expect irregularities in the background on scales 10 to 100 times larger than this if galaxies formed in clusters. The main consideration in the first observational exploration of this question is the ability to reach flux levels of the sort mentioned in 2 together with an angular resolution of roughly 10 arc min or better.

4. Several topics of considerable current interest could be studied by means of a large telescope in space. To extend our knowledge of the deuterium abundance and distribution, it is important that the space telescope be able to reach 1215 Å. This is also desirable so that one can use resonance scattering as a probe for nearby intergalactic H I clouds. Resolution on the order of 0.1 arc sec would permit morphological classification of galaxies at modest distances and detection of galaxies at great distances. One would be very interested in a deep survey of angular position, magnitudes, and broadband colors of galaxies (to magnitudes well beyond 22) in sample strips some tens of arc minutes wide and several degrees long. This would probe the nature of clustering at great distances and how it may have evolved. Of fundamental importance to cosmology is the use of a space telescope to find and calibrate precise distance standards.

5. For the purpose of locating and studying the x-ray morphology of clusters at $z = 1$, x-ray observations at flux levels of 10^{-14} erg/cm^2 sec with angular resolution of 10 arc sec are needed.

6. Soft x rays of established extragalactic origin in the energy region below 1 keV provide one of the few tests—perhaps the only one possible—for a general, hot intergalactic plasma of closure density. Existing measurements can exclude only a range of postulated temperatures. Further progress will probably require a better understanding of the *galactic* soft x-ray emission.

7. The gamma-ray diffuse background should be studied to determine if its spectral shape is consistent with that predicted by red-shifted radiation from matter-antimatter interactions or primordial black holes. An instrument with an area-efficiency factor of about 0.2 m^2, an opening angle of 0.3 to 0.5 sr, and energy resolution of about 15 percent is appropriate.

4
Disciplinary Strategies

The previous chapter has demonstrated that many different techniques are needed to attack a particular scientific question. Progress in astronomy results from information transfer among the various disciplines as well as from discoveries in any particular one.

It must be kept in mind that the various facets of the universe appear to us in different parts of the spectrum. Since the stars appear in visible light, optical telescopes both on the ground and in orbit continue to be the backbone of astronomical inquiry. On the other hand, the superhot gases in the universe appear in x rays, so that x-ray telescopes see the extraordinarily active objects in the sky. The most violent regions in space accelerate electrons and protons up to nearly the speed of light, where their collisions with matter produce gamma rays. Thus, gamma-ray telescopes reveal the most violent activity of all. Relativistic electrons, upon encountering magnetic fields, emit radio waves, so that radio telescopes see the universe of relativistic electrons and magnetic fields, often concentrated around active and violent stars or galactic nuclei but also extending broadly through space. Finally, the excitation of various molecules in dense clouds and the heating of interstellar dust by stars and superluminous objects produces radiation in the submillimeter and infrared regions. Infrared and millimeter telescopes therefore show the extended cold and warm clouds in the universe, as well as a variety of curious centers of activity.

Apart from traditional optical astronomy all of these fields of observation are new, having sprung to life only with the advances in detectors and space technology of the last three decades. In each case the first fumbling, difficult exploratory observations were carried out with crude equipment to see if there was anything to see. In each case the first observations showed a wealth of signals from space. Improved instruments were developed, and with each a whole new realm was opened up. The radio, infrared, optical, ultraviolet, x-ray, and gamma-ray telescopes see different skies, each rich in its own unique, active, and exotic objects.

With these facets in mind, it becomes urgent that different telescopes be flown in the coming years, each telescope with the mission to explore its appropriate universe. The range of work to be done is so wide that in some cases the word "observatory" is appropriately appended to the basic mission, although the term does not mandate extremely long duration or high cost of the mission. However, in each field the range and quantity of objects to be studied is enormous, hence the longer the telescope can continue to observe the more cost-effective will be the mission.

The observations made by the different telescopes on the skies to which each is sensitive need to be closely coordinated, so that our insights concerning active stars, hot gases, fast particles, magnetic fields, and collapsed objects can be assembled into a single coherent picture.

The fact remains, however, that individual astronomers are rarely able to work at the frontier of more than a single discipline. Likewise, astronomical instruments and observatories can seldom serve the needs of more than one technique. Thus, in order to recognize the reality of the way in which astronomy is actually done and the way in which space missions must be planned, we have organized this chapter according to the strategic elements of each discipline.

LOW-ENERGY ASTRONOMY

Optical and Ultraviolet Astronomy

Optical astronomy is well developed compared with studies at other wavelengths. The entire sky has been surveyed from the ground at about 2-arc sec resolution and over an intensity range of 10^8. The main advantage of space observations in this wavelength range is the high spatial resolution that can be achieved. In addition, the background radiation is reduced especially for $\lambda >$ 7000 Å. Ultraviolet astronomy can be done only from space and is, as a consequence, much less explored. So far, the main achievements are low-resolution mapping and spectroscopy of bright objects from rockets, from OAO-2 and OAO-3 (the *Copernicus* satellite), and from the IUE.

The following provide some examples of the fundamental scientific problems that were discussed in Chapter 3 and that would substantially benefit from space observations in the ultraviolet and optical:

In the area of cosmology:

1. Establishment of a cosmological distance scale.
2. The geometrical properties of the universe. This question is best addressed through studies of galaxies in clusters at red shifts of $z > 1$.
3. Determination of the epoch at which heavier elements were synthesized.

In the area of galactic problems:

4. The nature and evolution of quasars and their relationship to galaxies.
5. The nature of the nuclei of galaxies and the origin of the energy released in active galaxies and quasars.
6. The physical and chemical properties of the interstellar medium in our own and nearby galaxies.

In the area of stellar problems:

7. The nature of binary x-ray sources and accretion disks.
8. The search for massive star remnants (black holes?).
9. Study of the faint end of the stellar luminosity function, especially in clusters.

While significant progress on some problems requiring ultraviolet spectroscopy of sources brighter than ~14th magnitude is being made by the IUE, the most exciting scientific questions require study of substantially fainter objects and the ability to observe at significantly higher spatial resolution than can be achieved (with high sensitivity) from the ground. As shown in Chapter 3, important advances can be made with spatial resolution of order 0.1 arc sec both in the study of resolved sources (e.g., galactic morphology) and in detection of fainter point sources ($m \geqslant 27$) against the background. In order to achieve such resolution, the Space Telescope aperture of 2.4 m is required. The light-gathering power of this telescope will permit moderate resolution ultraviolet spectroscopy ($R = 10^3$) of objects as faint as 18th-magnitude quasars and 20th-magnitude unreddened B stars and will yield low-resolution results to 20th to 25th magnitude, depending on wavelength range and spectrum. For extended objects, this telescope will also permit moderate-resolution ($R = 10^3$) spectroscopy to surface brightness of 15th magnitude per square arc sec if the full (0.1-arc sec) resolution is exploited. This will permit progress on essentially all the examples cited above.

Thus, the main requirement for a breakthrough in optical–ultraviolet astronomy is the 2.4-m Space Telescope (ST). Its 0.1-arc sec resolution will permit tremendous advances in discovery of faint-point objects, in high-spatial-resolution studies of higher-surface-brightness features, and in ultraviolet spectroscopy of sources down to $m = 20$ or fainter. It will strongly contribute to planetary investigations as well. This telescope is the overwhelming priority for optical–UV astronomy.

In view of the tremendous power and long life of the ST, it is clear that new approaches will be required to the management of the facility. The following areas are of particular concern:

1. Choice of scientific programs and their scheduling on the telescope,
2. Dissemination and analysis of data,
3. Choice and implementation of the new instruments for the telescope.

This subject has been discussed in detail by a special committee of the National Research Council and its general recommendations are endorsed by the Committee on Space Astronomy and Astrophysics.

Several other important components are needed in the optical–UV domain. Experience at ground-based observatories shows that a single large telescope must be supplemented in various ways. In particular, there is need for survey (i.e., wide-field) capability and for smaller instruments to carry out exploratory or developmental programs. Both of these activities have their space analogs, respectively, in a UV survey and in the need to make specific limited observations and/or develop and test new techniques or instruments for use with the ST. Such programs could be carried out with telescopes of approximately 1-m aperture and hence are well suited to Shuttle operations.

There will be a strong requirement for an intermediate-field ($>1/2°$), high-resolution ($\leqslant$0.3 arc sec) instrument to be used to provide survey information in fairly large but restricted areas at faintness levels not possible from the ground (i.e., when reduced sky background and high angular resolution are required). Examples are in studying stars in nearby galaxies (e.g., Cepheids) or in slitless spectroscopy of very faint objects (e.g., searching for faint radio quiet QSO's to be studied later with the ST). The number of resolution elements needed to cover this field exceeds 10^7 and accordingly requires photographic or electrographic recording. This is best suited to Shuttle operation.

A second important area that is not included elsewhere in the optical/IR program is the need to make spectroscopic observations at wavelengths shortward of 1150 Å. This spectral region is crucial for studies of molecular hydrogen and a number of important ions (C III, N II, for example) in the interstellar medium in our own and nearby galaxies. Observations between 950 and 1150 Å can be made efficiently if LiF-coated optics are used. Such coatings are not planned for the ST but could be included in a Shuttle facility on a special far-UV spectroscopy mission.

A third requirement is for an all-sky UV (~1500 Å) survey to complement the existing surveys in the visible. Such a survey would provide a wealth of fundamental data, which, when combined with optical data obtained from the ground, would give vastly improved color (temperature, spectral index, extinction) discrimination. It would also readily provide source lists of hot stars down to substantially fainter magnitudes than can be achieved even with U-band surveys from the ground. To carry out such a survey a wide-field (about $6^\circ \times 6^\circ$) telescope with 1-2 arc sec resolution and photographic or electrographic readout is required. Such a telescope would be used in the Shuttle mode. It would be adaptable to a number of other studies (e.g., surveys at other UV wavelengths or objective-prism spectroscopy).

The power of space observations can be improved in direct proportion to the detector sensitivity and number of resolution elements available. The routinely available quantum efficiency of photoelectric devices in the visible and near-UV regions can be improved from 10-20 percent to at least 40-50 percent. Charge-coupled devices have efficiencies up to 70 percent but so far are poor in the UV. The spectral range can be expanded, and the picture element size reduced by a factor of about 2. A strong development program is required in this area to improve present systems over the next few years.

For the longer range, and in preparation for missions beyond this decade, the following two prospects appear particularly exciting and merit early investigation.

LONG-BASELINE INTERFEROMETER

For more than 50 years, beginning with Michelson, astronomers have tried to achieve high angular resolution in order to measure size and structure of simple objects, by interferometrically combining images from increasingly widely separated apertures. With phase-coherent interferometry, only very limited success on a few bright objects has been achieved so far, mainly because the earth's atmosphere reduces coherence so severely between apertures that are more than a few meters apart. Radio astronomers, on the other hand, have developed the technique to a very high degree, using baselines of up to thousands of kilometers and observing structural details down to tenths of milli-arc seconds. These and other kinds of observations have shown the need for comparably high resolution at optical wavelengths for the study of stellar surfaces and shapes, close binaries, BL Lac objects, quasars, and other sources of very small angular size. Space observations will make long-baseline optical interferometry possible at any wavelength, since the wavefront from each of the separated telescopes is undistorted by atmospheric effects. Large collecting areas can be used, allowing the system to reach faint levels. Baselines of tens and ultimately hundreds of meters should be feasible, leading to sub-milli-arc-second resolution on faint objects. Exploratory work should be carried out first from the Shuttle (~10-m baseline) and, if successful, should lead to a larger facility.

LARGE-FLUX COLLECTOR

Orbital operation, with its freedom from weight, wind, and "seeing" problems, offers the possibility of putting up very-large-area flux collectors with imaging capability comparable with that of the ST, namely 0.1 arc sec. In principle, at such high resolution extremely faint objects (perhaps down to $m = 30$) could be detected; the problem lies in the extreme shortage of photons, which in turn can only be made up by going to a very large aperture. Thus, an instrument in the 10–25 m class is needed to exploit such high angular resolution to the fullest. The ST would be able to detect less than one photon per minute from a 30th-magnitude object, requiring prohibitively long exposures to build up good signal-to-noise ratio against the background. At least a tenfold and preferably a hundredfold increase in light-gathering power is needed for the next step. So large a flux collector will greatly exceed the size of the Shuttle and will have to be assembled in space. Hence, it will require a totally new approach to design and deployment if the cost is to be acceptable. Recent technological advances suggest that the latter condition can be fulfilled. Studies of appropriate techniques for achieving this goal need to be initiated soon, in preparation for missions in the 1990's.

The overall strategy in the near term therefore calls for the following:

1. The free-flying 2.4-m Space Telescope (ST) capable of 0.1-arc sec imaging, with an appropriate institute to coordinate its scientific operation and data handling.
2. Supporting programs for Shuttleborne survey observations and development of new focal-plane instruments.
3. Development of high-sensitivity two-dimensional detectors with high spatial resolution and coverage.

The future development of the subject suggests that the following possibilities be explored:

1. Development of a long-baseline (>20 m) optical interferometer for the study of faint, high-surface-brightness objects.
2. Deployment of a large (10–25 m) flux collector with 0.1-arc sec angular resolution.

Infrared Astronomy

Infrared astronomy reveals the cool component of cosmic matter—solids and molecules. Since cosmic solids are at temperatures between 3 and 2000 K, their emission peaks are in the infrared. Most of the vibrational and rotational transitions of molecules lead to emission in the infrared. Infrared observations are also one of the most important ways to study what appears to be radiation from the earliest stages of the universe. Most of the energy of the 3 K background falls in the millimeter and submillimeter regions. The energy released by primordial galaxies may be shifted in the present epoch into the infrared.

In the past 10-15 years, the sensitivity of instruments used for infrared astronomy has been improved by more than two orders of magnitude. As a result, exciting and important discoveries have been made, including

1. Stars at previously unexplored early stages of evolution;
2. Significant internal energy sources in the planets Jupiter and Saturn;
3. The demonstration that the spectrum of the 3 K cosmic background radiation has a peak consistent with its interpretation as the primordial blackbody radiation;
4. The emission of H II regions, which is dominated by thermal radiation from dust;
5. Galactic nuclei and other extragalactic objects that emit large amounts of energy in the infrared.

An appropriately implemented strategy for infrared astronomy will lead to another increase of our capabilities by two or more orders of magnitude over the next decade. The scientific goals have been described in Chapter 3. While many of the most important discoveries that will result from this expansion in capability cannot be anticipated, we can expect major advances in our understanding of

1. The earliest stages of the universe;
2. The formation and evolution of galaxies and other kinds of extragalactic objects;
3. The processes by which stars and planets form;
4. The growth of complex molecules in dense interstellar clouds;
5. The properties of planets and asteroids.

The need to make infrared observations from space arises because the environment of ground-based instruments imposes serious limitations due to background thermal emission, atmospheric absorption, and atmospheric instability. Between 3 and 120 μm, the limiting noise for most instruments arises from the thermal emission of the telescope. Cooled telescopes (operated in space to prevent condensation of atmospheric gases on the optical surfaces) offer enormous advantages over this spectral range. Atmospheric absorption is an overriding problem between 30 μm and 1 mm, as well as in a number of narrower spectral bands between 1 and 30 μm. Atmospheric turbulence limits the angular resolution achievable between 1 and 20 μm.

The ultimate limit to the sensitivity of a cooled telescope in space arises from the thermal background emitted by the dust grains also responsible for zodiacal light. In order that the telescope not degrade that limit, it must be cooled to about 50 K (e.g., with solid nitrogen) for operation from 5 to 20 μm and to about 10 K (e.g., with helium or solid hydrogen) for operation near 100 μm. For many applications, detectors are already available that could reach the zodiacal background over nearly all of the 5- to 100-μm spectral range. The required size of a cooled telescope is set as much by the desired angular resolution as by the sensitivity: the Rayleigh limit for an 0.5-m telescope is 5 arc sec at 10 μm and about 1 arc min at 100 μm. The higher resolution afforded by a 1-1.5 m instrument will be of crucial importance for many studies.

Ground-based and balloon- and airplane-borne telescopes will continue to be needed to provide flexibility for the successful planning of space observations and are essential for confirmation and followup studies of objects discovered from space. However, the future growth of infrared astronomy will come predominantly through space observations, for which four main capabilities are needed during the next decade:

1. A deep, all-sky survey for sources in the 10-200 μm regions, now in preparation with the IRAS satellite (launch in 1981);
2. Preparation of a cooled telescope of aperture 1-2 m, with the ability to conduct extended periods of observation with a variety of focal-plane instruments, for launch toward the end of the decade;
3. A small, free-flying satellite (Explorer class) dedicated to cosmological measurements, with emphasis toward a precise measurement of the spectrum and anisotropies of the 3 K background radiation and toward a search for primordial galaxies;
4. Absolute flux measurements or substantially improved upper limits in the 1-3000 μm range.

Important contributions in some areas (particularly spatial resolution and high-resolution study of spectral lines) will be made through use of large, ambient-temperature telescopes in space, such as the ST. A particularly important aspect to be investigated within the decade is the development toward spatial interferometers operating above the atmosphere for observations with very high angular resolution. An urgent need in infrared astronomy is the development of more sensitive detectors at wavelengths beyond 100 μm and of large arrays of detectors at all wavelengths. Work in this direction requires strong support to use fully the capabilities of cooled telescopes.

Radio Astronomy

The field of radio astronomy in the past has not been a prime activity of the space endeavor. Radio instruments are generally quite large, and the available scientific spacecraft were unable to transport competitive radio-telescope systems. The advent of the Space Shuttle eliminates this barrier to space activities in radio astronomy, and we anticipate that its use will, in time, make possible the world's best radio telescopes.

In spite of the highly developed state of radio astronomy, some of its most important programs suffer from severe limitations imposed by ground-based operations. Radio astronomy in space will lead to breakthroughs in at least three major areas:

1. The simultaneous operation of several radio receivers with variable baseline over very large distances to obtain the best possible image resolution (very-long-baseline interferometry);
2. Spectroscopy in that part of the millimeter and submillimeter wavelength range that is obscured by the atmosphere, to reveal the presence and nature of molecules and chemical processes taking place in interstellar and circumstellar clouds;
3. The construction of very large collecting areas of high mechanical precision in an environment free of gravitational and wind-loading forces.

Within our ten-year program falls the deployment of a small pointed radio telescope of the order of 3-m size on the Shuttle. Its purpose will be to carry out very-long-baseline interferometry, with continuously variable baseline, in conjunction with one or more ground-based radio dishes. The resulting ensemble of baseline lengths and orientations will far exceed the ensemble that can be provided by a few telescopes fixed on the earth. Since the effective collecting area of an interferometer is proportional to the mean of the areas of the individual antennas, combining a 3-m antenna with, for example, the Arecibo antenna, yields an interferometer with reasonably high sensitivity.

To exploit space radio astronomy fully, the next decade should serve to define and begin an orderly program of steps. No thorough studies of the potential of radio astronomy in space have as yet been conducted by the community of radio astronomers. In this respect, space radio astronomy lags behind other fields. To identify clearly the scientific goals of radio astronomy in space, it is important that such a study be initiated in the near future. However, some of the long-range goals for space radio astronomy can readily be anticipated. The Space Shuttle, for the first time, provides the means of assembling large structures in space. Studies should, therefore, be pursued to develop a 100-foot radio dish of millimeter-wave precision to be assembled in space, free of gravitational distortion of the structures. This dish would serve two purposes: very-large-baseline interferometry with high sensitivity and molecular spectroscopy with high sensitivity. Access to the full range of millimeter lines, about half of which are shielded from our view by the atmosphere, will be a major gain.

As the techniques for fabricating extremely light-weight, low-cost large structures in space develop rapidly during the coming decade, plans need to be prepared for the deployment of a pointed radio telescope several kilometers in diameter. An instrument with this nearly two-orders-of-magnitude increase in collecting area over the largest ground-based telescope would not only widen our horizons enormously but would almost certainly lead to discoveries not yet predicted or imagined.

HIGH-ENERGY ASTRONOMY

X-Ray Astronomy

X-ray astronomy, now in existence for 15 years, has become a major component of the physical sciences. A number of satellite experiments have revealed x-ray emission to be a pervasive feature of a broad class of astronomical phenomena, certain of which are fundamental to advancing our understanding of the nature of the universe.

One major thrust of the space-astronomy program is to bring x-ray astronomy to its full potential, namely, the capability to produce images of 1 arc sec or better, spectral measures with resolution of 10^3, a dynamic range of 10^8 between brightest and faintest detected objects, high-resolution timing observations, and a host of more specialized capabilities. Most of what we know about astronomy as expressed in Chapter 3 comes from the fact that optical and radio astronomy have had this kind of capability for many decades. And the expectation is that results from x-ray astronomy can vastly expand our knowledge of the universe if this goal is met.

Of prime importance to future progress in this field is the fact that focusing telescopes with all their potential for high-quality data can be used in the x-ray domain. This provides the basis for the major recommendation in this area, namely, the development of a telescopic mission that will function as a national facility.

Many objectives of high importance, however, cannot be met with telescopes. For example, the measurement of intensity variations over a wide range of time scales, which offers the potential of establishing characteristics of neutron stars and black holes, needs to be incorporated into an Explorer mission of limited scope dedicated to timing measurements.

With the completion of the HEAO-1 survey, the number of known discrete sources of x radiation should be about a thousand. There is also a substantial flux of background x-ray radiation. One component, which is more or less isotropic, extends to high energy and must be of extragalactic origin; another component, which is seen below 1 keV, is associated with the galaxy.

The list of objects seen to be discrete sources reads like the index of an astronomy textbook. With the possible exception of cool, single stars and cold gaseous regions, virtually every kind of astronomical system has by now been found to be an x-ray source. Of key interest is the fact that specific objects of high intrinsic interest to several areas of astrophysics are prodigious x-ray sources. Neutron stars and probably black holes are very luminous x-ray sources, as are hot white dwarfs. These objects are at the end point of stellar evolution. Being fantastically dense, they offer a unique chance for studying the physics of dense matter and the general theory of relativity. Objects outside the galaxy, active galaxies—the Seyferts and the quasars—are seen to be x-ray sources, as are entire clusters of galaxies.

One reason for this widespread x-ray emission is now well understood. Gravitational fields provide a trap and energy source for hot plasmas, and it seems to be the case that an x-ray emitting plasma is present wherever gravity allows its containment. In the case of the neutron stars and black holes, the plasma is seen to originate as mass transfer from a companion star, and, in the case of clusters of galaxies, it may be swept out of the galaxies themselves. The other process that is well understood involves the interaction between cosmic rays, photons, and magnetic fields. This process is probably working in supernova remnants, pulsars, and other strong radio sources that are seen to be x-ray sources.

An important point is that not only are these objects x-ray sources, but also the information obtained from x-ray observations is unique. For example, data from the binary x-ray stars have allowed the determination of neutron-star masses, and data from clusters of galaxies have revealed the existence of an intergalactic medium and permit the study of its physical state. Other kinds of data extend substantially the information that we already have; for example, our understanding of stellar coronas and of stellar activity has been greatly enhanced by the observation of x rays from many types of stars.

Spectroscopy is another example of high-quality data now becoming available. Line emission from highly excited iron has been seen in many objects, including clusters of galaxies, and instrumentation on HEAO-2 should be capable of detecting line emission from various elements with resolution ($\lambda/\Delta\lambda$) of up to 10^3.

Many x-ray observations are still poorly understood. For example, while most of the x-ray bursters appear to be accreting degenerate neutron stars, there remains a prospect that black holes may be similarly involved. Another class of objects—weak x-ray sources at high galactic latitude—are quite puzzling.

Our present information has been obtained principally from a number of small satellites, one of which, SAS-3, is still fully operational. The first two of a new generation of satellite experiments, HEAO-1 and HEAO-2, have recently been launched. The instruments on several of these satellites use mechanically collimated detectors not dissimilar from those flown on sounding rockets during the early exploratory phase of investigation. A new class of instrumentation, based on the use of focusing optics, has been exploited in HEAO-2. These latter instruments offer improvements by orders of magnitude in sensitivity, spatial resolution, and spectral resolution over what is now available.

The recommendations for programs enumerated below are intended to extend significantly our understanding of important astronomical phenomena. These recommendations require that x-ray astronomy be adequately supported in the near term, otherwise the base on which future missions are predicated will disappear. Of particular importance is continued support of ongoing missions (such as HEAO-2) and the extension of their orbital operations as long as technology permits and as long as useful data are retrieved. Furthermore, the new missions recommended, even if started immediately, could not be operational until the mid-1980's. Therefore it is of crucial importance to the health and continuity of x-ray astronomy that the HEAO-2 mission be extended to the longest technically feasible lifetime. In parallel, adequate support is needed for instrument development in the laboratory and for specialized instruments on rockets and Spacelab.

A clear priority in x-ray astronomy is the development of a national facility telescope, patterned after HEAO-2 and making use of grazing-incidence x-ray optics. It appears feasible to prepare optics in the 1–1.5 m aperture range that would provide several times the collecting area of HEAO-2. Along with improved optics and focal-plane instruments, this mission would provide an order-of-magnitude increase in sensitivity per unit time over what is achievable with HEAO-2. The long life of such a facility extends its capability further. The great improvement in sensitivity, the ability to address problems of fundamental importance, the potential for new discovery, and the availability of observing time to a broad range of users combine to make this mission a key feature of the nation's astronomy program, not just that of x-ray astronomers.

Other major goals have been identified in the discipline, involving more specialized instrumentation. It is possible that several experiments can be grouped together to form a single mission, following the pattern of HEAO-1. Experiments in this category include observations above 4 keV, polarimetry, certain kinds of spectroscopy, and all-sky monitoring activities. Also, other facility-type instruments can be designated that make use of optics. One example is a mission that maximizes telescope aperture and field of view at a sacrifice of angular resolution, the principal objectives being very deep surveys and very fast timing observations.

Important x-ray objectives can be met through intermediate missions as represented by Explorers and Spacelab opportunities. As has been noted, timing measurements cannot be suitably carried out on telescope-based facilities. The principal technical requirement is for large detector area because instantaneous data rate is a key factor. Since strong sources are to be observed, background is not a serious factor. The opportunities for fundamental advances in understanding the end point of stellar evolution and the physics of dense matter through these observations are unique in astronomy. For example, many strong x-ray sources in binary systems are found to be pulsing with periods ranging from less than 1 sec to several minutes. These characteristics have been taken to be a positive signature of a neutron star and offer one of our best opportunities for probing the properties of dense matter in general and neutron stars in particular. A similar class of sources exist that do not exhibit pulsations but rather show irregular intensity variability down to the millisecond time scale. Cygnus X-1, the most credible black hole candidate yet detected, is in this category, and there is a suspicion that other black holes may be lurking among these objects.

Another type of x-ray investigation well suited to specialized instruments entails the study of iron line emission. This feature has proved to be pervasive among x-ray sources and is of high scientific interest. Studies of the x-ray emission of the interstellar medium also fall in this category.

Spacelab affords two distinct kinds of opportunities for x-ray astronomers: one is the pursuit of scientific objectives of high interest that can be accomplished within the limited time frame of the Shuttle (7-30 days), the other is the development of new technology and new observational goals. Examples abound of both—studies of x-ray bursters, spectroscopic and polarimetric investigations, new kinds of x-ray telescopes, surveys of restricted spectral or spatial domains, all fit within this category. X-ray astronomers could become among the more prolific and productive users of the Shuttle capability, and this activity must be encouraged. Furthermore, the Spacelab opportunities provide an effective means of defining instruments and goals for larger, more expensive missions and allow for an efficient utilization of limited resources.

Gamma-Ray Astrophysics

The significance of gamma-ray astrophysics lies in its ability to reveal the explosive, high-energy, and nuclear phenomena of the universe. Thus, being the indicators of change and evolution, gamma rays provide special insight into the "how" and "why" of the physical processes that govern our universe. In addition, since gamma rays have a low interaction cross section, gamma rays have a very high penetrating power and can reach the earth from very distant parts of the universe, as noted earlier. In contrast to optical photons, only the total amount of matter, not its form, is relevant for gamma-ray interactions. However, the earth's atmosphere has too much total matter for gamma-rays to reach the earth's surface in the primary form. Still more important, the interaction of cosmic rays causes the atmosphere to be a bright source of background gamma rays. Hence although the many positive aspects of gamma-ray astronomy had long been recognized, the low intensity of gamma rays and the need to be above the earth's atmosphere caused the first detection of celestial gamma rays to be delayed until the 1960's. Now, particularly with the results of the SAS-2 and COS-B satellites, gamma-ray astrophysics has proceeded from the discovery phase to the exploratory phase. These results have shown the rich character of the galactic-plane diffuse emission with its potential for the study of the forces of change in the galaxy, the origin and expansion of the cosmic-ray gas, and galactic structure. Moreover, with the observations of discrete sources, some associated with supernovae and pulsars and others apparently not correlated with radiation at other wavelengths, point-source gamma-ray astronomy has also begun, and it offers the opportunity of studying the most dynamic nonthermal processes occurring in stellar objects, including such phenomena as relativistic particle acceleration, nucleosynthesis, and very-high-energy shock waves. There will then be the opportunity of having direct information on the processes occurring in neutron stars, black holes, pulsars, and supernovae.

The universe is largely transparent to gamma rays, and this transparency extends back to the early stages of the universe. This feature together with the intrinsic high-energy character of gamma rays means that there are especially promising windows for the study of active galaxies and observational cosmology. The detailed study of the general celestial diffuse gamma radiation, for example, will provide a direct test of the symmetric big bang theory.

The immediate scientific goals can be summarized as follows:

1. A study of the dynamic, evolutionary forces in compact objects such as neutron stars and black holes, as well as gamma-ray emitting objects whose nature is yet to be understood.
2. A search for evidence of nucleosynthesis—the fundamental building process in nature—particularly in the environment of supernovae.
3. The exploration of our galaxy in the gamma-ray range particularly with regard to regions difficult to observe at other wavelengths, the origin and dynamic pressure effects of the cosmic rays, and structural features particularly related to high-energy particles.
4. The study of the nature of other galaxies in the high-energy realm and especially the extraordinary ones such as radio galaxies, Seyfert galaxies, and QSO's.
5. The study of cosmological effects through the detailed examination of the diffuse radiation and the search for primordial black hole emission.

These scientific goals require a set of large individual experiments that may advantageously be combined into a free-flying spacecraft of major payload capability. The immediate next step, therefore, calls for a complement of instruments to be incorporated into a gamma-ray observatory that includes the capability to carry out the following:

1. A survey of gamma-ray sources and diffuse emission with a point-source sensitivity of 10^{-7} photon cm^{-2} sec^{-1} or better, angular resolution of 8 arc min for strong sources, and energy resolution around 15 percent at energies above ~30 MeV.
2. A survey of gamma-ray sources and diffuse emission with sensitivities around 10^{-5} photon cm^{-2} sec^{-1} and energy resolution around 25 percent at energies between 0.1 and 30 MeV.
3. Detection and identification of nuclear gamma lines with an energy resolution of <0.4 percent and sensitivity of the order of 10^{-5} photon cm^{-2} sec^{-1}. The initial subjects of observation will be the interstellar medium and supernova shells.
4. Observations of gamma-ray bursts, studies of their spectral and temporal behavior, and locations of the sources to 0.1 deg.

The technology to build the appropriate instruments exists, and the development has already progressed to the point where construction of flight units can occur.

Experience has shown that the various branches of modern astronomy are synergistic. A lack of advancement in any area, especially one such as gamma-ray astronomy, which is both unique and just about to take a major step, causes problems to remain unsolved and work to proceed in other than the best directions. A comprehensive gamma-ray mission is now urgently needed for an astrophysics program that will achieve significant progress on the central problems of astrophysics.

With the gamma-ray sky surveyed in some depth with the gamma-ray observatory, it will then be possible to concentrate on detailed features of discrete sources and limited regions such as clouds, galactic arms, and nearby galaxies. The character of the expansion forces, high-energy processes, nucleosynthesis, and cosmic relativistic particles should then be revealed in great depth. The full solution of problems related to galactic dynamics, compact objects, supernovae, and the nature of radio galaxies, quasars, and other truly exceptional objects will be accomplished by combining these unique gamma-ray astronomy results with information from other wavelengths.

In a mission subsequent to the gamma-ray observatory, a high-energy telescope is needed that will concentrate for long periods of time on particular sources and limited regions of the sky of special interest. This is necessary to accumulate the statistical volume of data required to resolve spatial and spectral features of the sources in satisfactory detail and to study temporal variations continuously over periods adequate to decipher complex dynamic behavior. The field of view of the telescope does not need to be wide, but a large collecting area is essential and should be on the order of 3 to 10 m^2. This instrument will study single sources or small regions long enough to define some spectra up to 10^{11} eV. Angular resolution for sources should be optimized to the extent possible, with the target being of the order of 1 to 2 arc min. A high-resolution nuclear gamma-ray spectrometer is also required for in-depth study of the gamma-ray lines from such processes as radioactivity in supernova remnants, positron annihilation in the galactic disk or extragalactic interactions, lower-energy cosmic rays passing through dense matter, and nucleosynthesis in violent events in distant galaxies. Sufficient energy resolution to study line profiles will be desired together with a sensitivity in the range of 3×10^{-6} to 10^{-6} photon cm^{-2} sec^{-1}. Good angular resolution is difficult in this energy range, but it should be a goal of any design to achieve it as well as possible. This second gamma-ray observatory mission should be firmed up and flown as soon as a clear picture develops from the results of the first gamma-ray observatory.

In view of the major potential of gamma-ray astronomy for contributions to a wide range of astrophysical problems and the ultimate need for even more sensitive instruments of improved accuracy, the development of new and improved detector systems is a key part of the gamma-ray astronomy program over the next decade. High-sensitivity instruments (several m^2) with good angular accuracy (<0.1 deg) will be especially important for point-source and extragalactic studies. Improved energy resolution, particularly for gamma-ray line spectroscopy is needed to exploit the full potential of this field.

The Shuttle sortie mode, wherein instruments are carried into space for a few weeks, offers the opportunity of specific studies of selected objects in detail and also of thorough study in a space environment of the response of limited versions of the very large, complex instruments to be flown on a free-flyer. Instruments with good spectral resolution for gamma-ray lines and instruments with high sensitivities for high energies are clearly of particular interest. It is envisaged that there would be a continuing program in which new gamma-ray instruments would be flown to study specific objectives. Observations that are specific and one-time and observations of new objects found in other wavelengths for phenomena predicted in the gamma-ray regime are examples of possible investigations.

Cosmic-Ray Astrophysics

Cosmic rays have a dual role in astrophyics. Cosmic radiation is an important channel of astrophysical information about stars and other astronomical objects; and the cosmic-ray gas is itself an interesting astronomical "object" playing an essential role in various astronomical settings.

As one of many forms of radiation emitted in stellar processes, cosmic rays carry information that complements that carried by electromagnetic radiation. The cosmic rays are a unique sample of material from outside the solar system that bring direct evidence of nucleosynthesis processes and particle acceleration occurring in unusual events that are objects of wide astrophysical interest.

As an astronomical "object," the cosmic rays pervade our galaxy and other galaxies. They are an important constituent of the interstellar medium, along with gas, dust, and magnetic fields. The energy contained in the cosmic rays and the pressure that they generate are important in determining the structure of galaxies.

There are a number of significant astrophysical questions whose answers are likely to come, at least in part, from cosmic-ray observations. With respect to *stellar processes*, they address the synthesis of elements and the astrophysical sites and mechanisms of particle acceleration. With respect to *interstellar processes*, they address the questions of the heating, ionization, and clumping of the interstellar gas, and the galactic confinement of the cosmic rays themselves.

Cosmic rays are unusually energetic particles that must originate in unusually energetic astrophysical processes. Supernovae are likely sites for the origin of cosmic rays—the supernova explosion itself, the expanding cloud of the supernova remnant, or the pulsar that is sometimes the stellar remnant of the supernova. Supernovae are likely sites for major stages of nucleosynthesis. They accelerate at least electrons to very high energies (as evidenced by synchrotron radio emission) and are likely birthplaces of neutron stars and black holes.

Measurements of the composition of the cosmic rays, particularly isotopic composition, could provide critical tests of models of explosive nucleosynthesis. They may probe conditions deep inside the exploding star, near the "mass cut" that separates the material expelled into interstellar space from that which falls into the compact stellar remnant.

The particle acceleration process is not at all well established. Does it principally accelerate recently synthesized material from deep inside the exploding star or mainly unprocessed material from other regions? On what time scale does the acceleration occur? If processes that account for acceleration of the bulk of the cosmic rays (around 0.1 to 10 GeV/amu) are described, to what energy must those processes extend before other processes may take over? Measurements of cosmic-ray composition including abundances of isotopes that decay only by K-capture and of unstable elements such as the actinides, and the high-energy spectra of elements, can provide decisive answers to these questions.

The heating and ionization of the interstellar medium would be affected significantly by a large flux of low-energy cosmic rays. The measured cosmic-ray flux at energies greater than about 1 GeV is insufficient to produce much of the required ionization, but at lower energies, below about 0.2 or 0.3 GeV, the interstellar cosmic-ray flux is unknown because solar modulation excludes these particles from the inner solar system. To detect low-energy cosmic rays in the vicinity of the sun, direct measurements outside the solar cavity are required.

Since the cosmic rays constitute an essential ingredient of the interstellar medium, an important astrophysical question is the determination of the nature and location of the volume that contains the cosmic rays. Several of the isotopes that are produced during the propagation of the cosmic rays are radioactive with half-lives comparable with the expected confinement time. Measurements of abundances of these isotopes and of the variation with energy of the ratio of secondary to primary elements will address these confinement questions.

Electrons and positrons play a special role in cosmic-ray astrophysics because of their strong interactions with photons and magnetic fields. The production spectrum of the positrons can be accurately calculated from measured cross sections and the measured proton spectrum. Comparison of the positron-observed spectrum with the calculated production spectrum would yield unique information on the confinement time. In particular, positrons around several tens of GeV are produced by photons around several hundreds of GeV; thus models of energy-dependent cosmic-ray confinement that attempt to explain observations of high-energy nuclear secondaries must meet severe tests imposed by positron observations.

The variety of astrophysical questions sketched above require the following aspects of cosmic-ray astrophysics to be addressed in the coming decade:

1. Determination of the isotopic composition of cosmic-ray elements with $Z \leqslant 28$ from a few MeV/nucleon to about 10 GeV/nucleon.
2. Detailed measurement of the elemental composition for $Z > 28$.
3. Measurement of the elemental compositon for $Z \leqslant 28$ at very high energies (10 GeV/nucleon $< E <$ 10^4 GeV/nucleon).
4. Measurements of flux, spectra, and elemental composition of low-energy cosmic rays ($E <$ 200 MeV/nucleon) in deep space (a) in the ecliptic and (b) at high heliographic latitude and over the sun's poles.
5. Determination of the energy spectrum of positrons with energies $E =$ 200 GeV.
6. Searches for superheavy elements, antinuclei, and other still-undetected particles are likely to continue as by-products of some of these investigations.

The cosmic-ray studies in the next decade, therefore, require parallel development of several kinds of "principal-investigator-class" instruments. Already under way are balloonborne experiments in each of these areas as well as experiments on isotopic composition for ISEE-3 and experiments approved for HEAO-C (1979) and on ultraheavy elements for HEAO-C. It is important that the balloon program continue to support development of new instrumentation and that approved missions like ISEE-3 and HEAO-C be continued with their orbital operations extended as long as useful data are being obtained. High-energy experiments would appear to make best use of Spacelab opportunities and should fly at the earliest opportunity. Isotope experiments on balloons must be continued in order to develop and demonstrate the required resolution (mass resolution of about 0.2 amu) and at the same time derive scientific results for the more abundant elements. Spacelab opportunities are similarly valuable for the development of isotope experiments. These lead into the first major step for nuclear composition studies, which requires a large free-flying spacecraft with a two-year lifetime, carrying experiments for isotopes (few tenths m^2 sr, $\sigma = 0.2$ amu), high-energy elements to about 10^4 GeV/amu (few m^2 sr), and ultraheavy elements (at least 10 m^2 sr, charge resolution = 0.2 charge unit). The flux and spectrum of positrons above 200 MeV has been explored only in balloon work with results limited by statistical accuracy. Measurements to several hundred GeV are needed and require a magnetic spectrometer in a large instrument, initially on Spacelab and finally on a free-flyer.

In situ measurements of the composition of solar-flare particles and of galactic cosmic rays in deep space serve to probe the dynamics of interplanetary space through the study of particle transport and the total energy density of energetic particles in nearby interstellar space. Current work in these directions is carried out on the space probes Pioneer 10 and 11 and on the two Voyagers. Extended, postencounter mission phases are a requirement for the particle instruments probing the heliosphere. An important goal for the next decade is the exploration of interplanetary space at high heliographic latitude and over the solar poles. Since most features of the solar system are not expected to be spherically symmetric, entirely uncharted ground will be covered. Energetic particles play an important role in this exploration, and access to the low-energy interstellar particle population may be achieved.

The decade's requirements in cosmic-ray astrophysics therefore include the following components:

1. A large free-flying cosmic-ray observatory carrying a complement of individual experiments.
2. Opportunities for at least three classes of experiments (high-energy, isotopes, positrons) to be carried on Spacelab.
3. Continued availability of high-altitude balloon flights at various geomagnetic latitudes.
4. Low-energy particle measurements at high heliographic latitude and over the solar poles.
5. Continued opportunity for deep-space observations in conjunction with

inner-planet and outer-planet missions, including viable postencounter, extended-mission data retrieval.

6. Experiments on Explorer-type spacecraft for precise determinations of isotopic compositions outside the magnetosphere.

Looking to the following decade, we can see requirements for substantially larger instruments to measure elemental composition to 10^6 GeV/amu (overlapping ground-based air-shower measurements), to measure isotopic composition of ultraheavy elements, and to measure isotopic compositions (for $Z \leqslant 28$) at higher energies. All of these goals will build upon developments occurring over the next 10 years, including both new astrophysical data and instrumental techniques.

SOLAR ASTRONOMY

The sun exhibits a wide variety of phenomena ranging from the relatively cool and static photosphere and chromosphere to the very energetic occurrences associated with solar flares. This results in a wide range of emission, spanning 14 decades in wavelength from radio waves to gamma rays, making the sun an object to which all observational disciplines contribute. Who would have expected a G2 main sequence star to be an object with high-energy astrophysical aspects? The study of the sun is unique in astrophysics because of its immediate impact on the human environment, and it is one of the few cases for which astrophysical mechanisms can be studied in detail, at close range and often *in situ*.

The period of rapid new discoveries in solar physics is behind us; much of present solar research is focused on the hard and tedious task of the precise understanding of a dynamic stellar atmosphere, thus making it a relatively mature science. This is even to some extent the case in the developing observational disciplines using x rays, XUV, and EUV radiations. The areas of solar gamma-ray, neutron, and neutrino physics are, however, completely exploratory, as is the study of behavior of the solar envelope away from the ecliptic plane.

The main components of the solar space program have been the rocket program, the Orbiting Solar Observatory program, and the Apollo Telescope Mount on Skylab. The solar space program in the last decade has concentrated on the exploration of the solar atmosphere. Major discoveries have been made, including: (a) the coronal holes, low-density regions in the corona responsible for the high-speed solar wind streams and for the geomagnetic storms; (b) the gamma-ray emission lines resulting from particle acceleration in flares and surface nuclear reactions; (c) the abundance anomalies in flare cosmic rays, especially the very abnormal $^3He/^4He$ ratio; (d) the existence of a very hot coronal flare plasma with temperature of ~20 million degrees located in soft x-ray loops and probably intimately related to the as yet unknown flare process; (e) the impact of coronal transients on the overall structure of the solar envelope; (f) the realization that the transition region between the chromosphere and corona is only a few hundred kilometers thick; and (g) the rapid variation of the hard x rays from flares and their dual character as being thermal and nonthermal. Much of the research has resulted in a vastly improved understanding of the physics of the solar atmosphere. The Solar Maximum Mission, scheduled to operate between 1979 and 1981, is the first solar mission dedicated to a single major problem—the action and origin of solar flares.

Problem areas in which future progress can be expected through space experimentation include the following:

1. The interaction of solar plasmas and magnetic fields,
2. Solar flares,
3. The energy transport in the solar atmosphere, and
4. The behavior of the extended solar envelope and the solar wind.

The outstanding instrumental requirement for progress on most of these is a continuing increase in spatial resolution that will permit observing the phenomena at new characteristic scale lengths, defined by theoretical predictions or by previous discoveries. In many instances the objects of study occur frequently and have short lifetimes. The short-duration flights of the Space Shuttle therefore suffice for these solar studies. The Shuttle, in fact, provides an ideal opportunity for early and inexpensive flight of instruments for specific or exploratory observations, for technique development, and for a class of instruments that evolve into a facility available to many users.

Several devices, such as the hard x-ray imaging system, the solar optical-UV telescope, and a grazing incidence XUV, EUV telescope are particularly suitable for evolution from a basic instrument of relatively modest cost into a versatile facility of considerable capability.

Of particular interest are the plans for a diffraction-limited Shuttle Solar Optical-Ultraviolet Telescope. This 125-cm-aperture device will be capable of resolving 0.1-arc sec (70-km) structures in the solar atmosphere, thus bringing within reach of the solar physicist the most interesting energetic phenomena in the solar atmosphere that occur on scales comparable with or smaller than the scale height in the solar atmosphere (~150 km). Such phenomena include the temperature rise to coronal temperatures that occurs on a scale of about 100 km; most or all of the surface magnetic fields, which are concentrated in knots of this size; most of the photospheric motions, which occur on scales not yet resolved by the best ground-based telescopes; flare instabilities predicted by solar-flare theories to be well below the present resolution limits; and kinematic energy transport in sunspots, which occurs on scales of 10–100 km. The telescope will cover the spectral range from 10000 to 900 Å and possibly beyond. Its high-resolution capability extends therefore to all layers of the solar atmosphere from the lower photosphere observed in visible radiations to the chromosphere transition region and corona to be studied in UV emission lines. The hot, 20-million-degree solar-flare plasma will be observable by means of the near-UV Fe XXI line. The 0.1-arc sec spatial resolution is 3–30 times better than that which has been previously achieved.

A definitive study of the solar mass loss through the solar wind will only be possible by sampling the particle flow and by the measurement of the magnetic fields at all heliographic latitudes rather than just near solar equatorial latitudes. The Solar Polar Mission has this as one of its main goals. It consists of two spacecraft that will travel in opposite paths in orbits over the two solar poles starting at a point near Jupiter. The other main goal of the mission is the study of galactic cosmic rays. Travel over the solar poles may well result in an uninhibited view of the cosmic rays that reach the solar system from our galaxy but that cannot penetrate the solar system down to the ecliptic because the complex magnetic-field structure at low heliographic latitudes disturbs the propagation of these cosmic rays.

The Solar Polar Mission is a truly interdisciplinary venture. Apart from the solar physics, space physics, and galactic cosmic-ray studies, it provides an ideal opportunity for the precise determination of the location of gamma-ray sources by means of triangulation, for the study of the propagation of radio bursts and their exciters in the circumsolar region, and perhaps for the study of interstellar dust. But above all, the Solar Polar Mission will give the unique data necessary for a major advance in our knowledge of cosmic-ray astrophysics and solar-wind physics. The next minimum of solar activity expected around 1987 would be ideal for such a mission because of the maximum amount of heliographic variation to be expected at that time and because the solar-wind temporal variations are largest then.

In addition to the Solar Shuttle Telescope and the Solar Polar Mission, there are several other spacecraft under study at present, including (a) a solar probe that will study the solar gravity field and the inner solar wind, (b) a mission to fly simultaneously with the Solar Polar Mission to provide a stereoscopic view of the solar corona, (c) a mission aimed at the study of long-term solar variability associated with solar activity and the solar cycle and at the relation between solar variability and the earth's environment, and (d) a dual spacecraft called the solar pinhole telescope that aims at giving high spatial resolution gamma-ray images of solar flares. These proposed spacecraft should be studied further to establish their technical feasibility and their potential payoff in terms of new astrophysics. In the long term, solar astronomy should also look forward to the solar maximum of 1991, when, after a decade of analysis and interpretation of the Solar Maximum Mission and Shuttle Telescope data, the time will be appropriate for another attack on the flare problem using the advanced instrumentation developed during the Shuttle era.