A New Science Strategy for Space Astronomy and Astrophysics

Committee on Astronomy and Astrophysics, Space Studies Board, Board on Physics and Astronomy, National Research Council

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Task Group on Space Astronomy and Astrophysics
Committee on Astronomy and Astrophysics
Space Studies Board
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Foreword

In 1991 the National Research Council issued a detailed strategy for astronomy and astrophysics for the next decade,[1] prepared by a committee under the leadership of John Bahcall. Like previous decadal studies in this field, the report identified in priority order the most important scientific programs and projects for both groundand space-based research. It recommended a single large initiative for space, the Space Infrared Telescope Facility, which now appears to be getting under way, albeit on a smaller scale than was originally envisaged.

The Bahcall committee members recognized that preparations for any subsequent space missions would have to begin during the second half of the decade, before the next decadal study. They recommended a series of technology initiatives that could lead to definition of subsequent missions. Although changes in the budget and philosophy of NASA have occurred since 1991, the schedule of events remains approximately as they foresaw.

The present report of the Task Group on Space Astronomy and Astrophysics, the Committee on Astronomy and Astrophysics, and the Space Studies Board represents a mid-decadal review of the most important and timely priorities in space astrophysics for the early years of the next decade. The topics described here have a high potential for breathtaking discoveries that will excite both scientists and the public. As the Bahcall committee report did in 1991, this report also recognizes fiscal realities by making difficult choices among many excellent initiatives. It should inform NASA and its own advisory committees as they update the agency's strategic plan for space science.

CLAUDE R. CANIZARES, CHAIR

SPACE STUDIES BOARD

[1] National Research Council, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991.

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Executive Summary

The half-decade since the publication of *The Decade of Discovery in Astronomy and Astrophysics*, the 1991 report of the National Research Council's (NRC's) Astronomy and Astrophysics Survey Committee chaired by John Bahcall, has been one of the most productive periods in the history of astronomy. Remarkable advances in understanding have been achieved, in no small part owing to the successful operation of space facilities such as the Hubble Space Telescope (HST), the Compton Gamma-Ray Observatory (CGRO), and several smaller missions including the Cosmic Background Explorer (COBE). The community consensus embodied in the Bahcall and earlier decadal surveys has proved to be a major factor in the initiation of many of NASA's space astronomy missions. But at a critical phase in NASA's planning cycle and midway between decadal surveys, the list of unexecuted consensus missions was too small to serve as the foundation for NASA's next strategic plan for the space sciences. Accordingly, in December 1995, NASA's Office of Space Science (OSS) requested that the Space Studies Board (SSB) update the scientific priorities for space astronomy and astrophysics in the context of recent discoveries and the likelihood that all but one of the space missions recommended by the Bahcall report will have been started before the year 2000.

To undertake this study, the SSB early in 1996 established the Task Group on Space Astronomy and Astrophysics (TGSAA), under the aegis of the NRC's Committee on Astronomy and Astrophysics (CAA). To encompass the wide range of topics relevant' to a study of astronomy and astrophysics beyond the solar system, TGSAA organized itself into four panels: Planets, Star Formation, and the Interstellar Medium; Stars and Stellar Evolution; Galaxies and Stellar Systems; and Cosmology and Fundamental Physics. Forty-six experts (including 10 of the CAA's 13 members) were selected to serve on these panels. The work of the four panels was coordinated by a steering group consisting of the chairs of the four panels, the two co-chairs of the CAA, an at-large member, and the chair of TGSAA. From among the leading topics for study identified by each of the four panels through debate, discussion, and a series of ballots, the steering group established a draft series of final priorities based on scientific goals. These priorities were later ratified in the same way at a joint meeting of TGSAA's steering group and the CAA. Thus, as input to OSS's development of its 1997 strategic plan, this report poses and prioritizes what TGSAA considers to be the most important scientific questions for researchers in space astronomy and astrophysics to address during the remainder of this decade and the beginning of the next.

Astrophysicists employ a broad variety of tools to study electromagnetic radiation over the entire spectrum as well as energetic cosmic ray particles. As a result of this diversity of techniques, TGSAA considered a wide range of space-based astrophysical opportunities. From among the many options, TGSAA identified four particularly important and timely priorities in space astrophysics for the early years of the coming decade. In ranked order these recommended priorities are as follows:

1. **Determination of the geometry and content of the universe by measurement of the fine-scale anisotropy of the cosmic microwave background radiation**;
2. **Investigation of galaxies near the time of their formation at very high redshift**;
3. **Detection and study of planets around nearby stars; and**
4. **Measurement of the properties of black holes of all sizes**.

The second and third priorities were given virtually the same weight.

Four additional scientific objectives were judged by TGSAA to be of high priority but to be less urgent at this time than the primary four listed above, or less achievable in terms of possible space missions. These recommended secondary objectives, unranked, are the following:

1. **Study of star formation by, for example, high-resolution far-infrared and submillimeter observations of protostars, protoplanetary disks, and outflows**;
2. **Study of the origin and evolution of the elements**;
3. **Resolution of the mystery of the cosmic gamma-ray bursts; and**
4. **Determination of the amount, distribution, and nature of dark matter in the universe**.

TGSAA places determination of the fine-scale structure of the cosmic microwave background radiation at the top of its list of priorities because of the enormous impact of COBE's observations. Not only have these observations provided confirmation of the hot big bang cosmological model, but they also have yielded new information on the primordial seeds responsible for the large-scale distribution of matter in the universe. Moreover, there is a very strong likelihood that moderate follow-on missions with higher-resolution instruments can, in the fairly near term, solve some of the deepest, and hitherto intractable, problems of cosmology and physics. TGSAA believes that NASA would be making a mistake of major proportions if it did not thoroughly and vigorously exploit the great breakthroughs achieved by COBE. The required observations are clearly defined, the necessary technology exists, and the costs appear to be fairly modest and well constrained.

TGSAA's recommendation for the study of galaxies near their time of formation in the early universe has a similar motivation. HST's observations in this field and in deep extragalactic research, in general, have been especially successful. Studies performed by HST and the Keck 10-meter, ground-based telescope are providing researchers with their first direct look at the evolution of galaxies only a few billion years after the beginning of the universe. Astronomers now have, as never before, the ability to build instruments allowing detailed observation of galaxy formation—one of the major missing links in current understanding of cosmic evolution. Additional work in this field will certainly be one of the central facets of astronomical research over the next few decades. Observations from space will be crucial to this enterprise, and the HST, the Space Infrared Telescope Facility (SIRTF), and possible successor instruments will be at center stage.

TGSAA's recommendation for a concerted search for extrasolar planetary systems and black holes should be intelligible to any reader of *Science* or *Nature*, or even the daily newspaper. At least 10 planets, all very massive compared to Earth, have now been detected around nearby stars. Study of these objects and many more can probably be conducted with optical or infrared interferometers in space. Such an endeavor will be a major scientific activity bridging the interface between astronomy, astrophysics, and the planetary sciences. TGSAA's recommendation for the detection and study of extrasolar planetary systems is a broad one, calling for a census of the most readily observed planets whatever their type. In TGSAA's judgment it would be premature to focus attention solely or primarily on terrestrial planets at this time. The detection and study of planets like Earth are very difficult tasks that should be viewed as constituting the culmination, not the beginning, of the process of extending our knowledge of planetary bodies beyond the confines of the solar system.

Black holes have long been thought to power the central engines of quasars and to be responsible for the x-ray emission from a handful of somewhat problematical binary stars. In the last few years these conjectures have been confirmed. Improved observations of active galaxies, combined with the discovery of new black hole candidates in binary systems, have brought about a wide consensus that black holes have, in fact, been detected. Confirmed examples have masses ranging from a few times that of the Sun, for those in binary systems, to about a billion times. greater, for those in active galaxies. Thus, within a few years, the status of these bizarre objects has gone from hypothetical entities predicted by general relativity—whose existence was doubted by many—to important constituents of the universe. A systematic study of black holes across the spectrum is extremely timely and, in the judgment of TGSAA, should be a central theme in space research during the coming decade.

Detailed justifications for TGSAA's recommended priorities are given in Chapters 2 through 5, each of which was contributed by one of TGSAA's four panels, and in the concluding Chapter 6. The panels' chapters discuss recent progress and current problems in a wide variety of astrophysical topics, among which the recommended priorities listed above are judged to be the most scientifically important, the timeliest, and the most plausible as the centerpiece of NASA's program in space astronomy and astrophysics during the start of the decade ahead. The additional key activities listed in Chapters 2 through 5 serve a number of roles, including providing scientific justification and support for small missions that could be proposed by individual principal investigators, offering guidance to peer-review panels that will select small missions, and suggesting a focus for technology development efforts that will enable future space astronomy and astrophysics missions.

Throughout its deliberations TGSAA assumed that all currently approved NASA astrophysical missions either would be operational by the early years of the coming decade or would be approaching launch. Missions of particular importance include the Advanced X-Ray Astrophysics Facility (AXAF), SIRTF, the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Far-Ultraviolet Spectroscopic Explorer (FUSE). Although TGSAA was not asked to make explicit recommendations about missions to address the scientific priorities outlined above, planned or proposed missions are implicit in the priorities recommended by TGSAA. Thus the Microwave Anisotropy Probe (MAP), approved by NASA while TGSAA's deliberations were under way, and the Planck mission (formerly COBRAS/SAMBA), a European Space Agency project with possible U.S. participation, are both dedicated to studying the anisotropy of the cosmic microwave background radiation.

1

Framework of This Study

ORIGIN AND RELATIONSHIP TO DECADAL SURVEYS

For the last three decades, U.S. astronomers have set forth their future plans and priorities in a series of so-called decadal surveys. Beginning in 1964 with the work of the Whitford committee and continuing with that of the Greenstein committee in 1972, the Field committee in 1982, and, most recently, the Bahcall committee in 1991, these reports have charted the future of astronomical research in the United States.[1-4] The decadal reports' approach to setting priorities is to define the means by which widely held, but unwritten, scientific priorities of the astronomical community are to be implemented. In other words, they prioritize in terms of projects and initiatives designed to address a broad range of community goals.

This report of the Task Group on Space Astronomy and Astrophysics (TGSAA) is not a decadal survey and does not replace the wider-ranging, consensus-building activities associated with the Bahcall report and its predecessors. TGSAA's deliberations were motivated by NASA's realization that there was a significant gap in the advisory foundation on which its Office of Space Science (OSS*) has to construct strategic planning priorities in space astronomy and astrophysics to be addressed in the first decade of the next century. This gap developed because of the rapid and successful implementation of several priority space missions, an unfortunate mismatch of schedules, and changes in the way government agencies are required to plan their future budgets.

In recent years NASA has adopted a systematic approach to strategic planning for all of its scientific activities, in part because of the changing environment for research funding and also in response to the requirements of the Government Performance and Results Act (GPRA) of 1993. Besides an agencywide plan, each of NASA's components, including OSS, must maintain its own long-term strategic plan. GPRA stipulates that, by the end of the decade, agency budget submissions to the Office of Management and Budget and to Congress must be formulated in terms of these strategic plans and performance plans based on them.

OSS currently revises its strategic plan every 3 years, with the next such update scheduled for the first half of 1997. At the same time, formulation of NASA's budget for FY 2000, the first year in which any major new space astronomy initiative could be proposed, will take place in early 1998.

The Bahcall report, issued in 1991, recommended a series of priorities for ground- and space-based astronomy

* Frequently used acronyms and those with lengthy definitions, together with definitions of selected terms and concepts, can be found in the glossary that follows Chapter 6.

and astrophysics projects. By the end of this decade, NASA expects to have fulfilled the report's remaining two priorities for space-based research in astronomy and astrophysics: initiation of the Space Infrared Telescope Facility (SIRTF) and completion of advanced studies of an astrometric interferometer facility. Thus, at a critical phase in NASA's planning cycle and midway between decadal surveys, the list of remaining consensus missions was too small to serve as the foundation of NASA's next strategic plan.

As part of its efforts to develop a new pool of missions from which a few with broad-based support might emerge, NASA canvassed the astronomical community for ideas by issuing a research announcement for proposals on new mission concepts in astrophysics.[5] From the resulting response, NASA chose some 30 mission concepts for advanced study, with the aim of selecting a few of the most promising candidates for development at a later date. To solve its more immediate needs for planning advice, NASA asked the Space Studies Board (SSB) to initiate the TGSAA study to identify new priorities around which OSS could build its 1997 strategic plan. The current absence of a consensus suite of well-developed mission concepts, such as the one in place at the time of the last decadal survey, mandated that TGSAA set priorities based on scientific goals. In other words, this report assesses current knowledge across a broad range of topics in space astronomy and astrophysics and then goes on to pose and prioritize the most important scientific questions that can be formulated at the present time. Thus, TGSAA's recommended strategy is not an implementation plan and is, in fact, independent of the means of implementation.*

It soon became clear in TGSAA's deliberations that the lack of emphasis on missions and the associated broadening of perspective meant that TGSAA's report would have an important secondary role as an adjunct or precursor to the next decadal survey. In essence the current report could be viewed as a framework around which the preliminary activities of the next survey committee could be organized.

RELATIONSHIP TO THE SPACE STUDIES BOARD'S OTHER SPACE SCIENCE STRATEGIES

Given the breadth of topics encompassed by space astronomy and astrophysics and the even wider range of scientific enquiries utilizing facilities and techniques usually associated with astronomical studies, it is not surprising that certain research topics fall within the spheres of influence of several different scientific communities. This compartmentalization frequently exists for bureaucratic reasons such as differences in the sources of funding; the danger is that certain areas of study can appear to "fall between the cracks." Failure to mention a particular topic in a report such as this thus does not necessarily mean that it is unimportant.

Areas of relevance to astronomy but not covered in this report include, for example, planetary astronomy and solar physics. The scientific priorities in these areas can be found in the reports of the SSB's committees on Solar and Space Physics (CSSP) and Planetary and Lunar Exploration (COMPLEX). Detailed discussions of topics such as helioseismology, solar neutrinos, and cosmic rays can be found in CSSP's *A Science Strategy for Space Physics.*[6] A more specific discussion of cosmic rays is contained in *Opportunities in Cosmic Ray Physics and Astrophysics.*[7] Topics relating to studies of planetary bodies and how planetary systems and life originate can be found in COMPLEX's *An Integrated Strategy for the Planetary Sciences: 1995-2010*.[8] Topics related to the Kuiper Belt and its relationship to circumstellar disks and the search for extrasolar planets will appear in COMPLEX's forthcoming report, *Exploring the Trans-Neptune Solar System.*[9]

APPROACH TO PRIORITIZATION

The basic goals for astronomy and astrophysics are many and varied. Observations of numerous objects in the universe make unique contributions to important scientific questions. Moreover, astronomy has a long history of major discoveries associated with the opening of new wavelength regimes and observing windows. Thus, it can be

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* The TGSAA study was not always completely divorced from studying missions. NASA did ask TGSAA to assess the projects selected for study under the aegis of the New Mission Concepts in Astrophysics program, but later withdrew the request.

argued that the best way to devise a science strategy for space astronomy and astrophysics is to consider the most important scientific questions to be tackled using each observing technique. Adopting this approach would greatly assist mission planners, in that the priority investigations for a particular mission proposal could be readily determined.

Organization by observing windows is, however, at variance with the multiwavelength character of today's frontline astronomical research. It is now common for researchers to specialize in the study of a particular class of astronomical object (e.g., active galactic nuclei) and their manifestations across the spectrum, rather than concentrating on the application of a particular technique (e.g., those of x-ray astronomy) to study a broad range of objects.

In summary, TGSAA's basic approach to prioritization was as follows:

- Concentrating on scientific objectives rather than emphasizing the methods by which the objectives are implemented;
- Adopting a multiwavelength approach by prioritizing scientific questions of significance to whole classes of astronomical objects and not limiting discussion to individual observing bands; and
- Being realistic with respect to such practical matters as cost and technical feasibility.

ASSUMPTIONS

For a variety of reasons ranging from redirected federal budgets and hardware failures to technological advances and changing scientific emphasis, the U.S. space program must remain flexible and alert to new opportunities. In addition, changing national policy goals can profoundly affect the resources available for space research, a recent example being the reconfiguration of the Advanced X-Ray Astrophysics Facility (AXAF) into AXAF-I and AXAF-S, followed by the termination of AXAF-S.

This report, like previous SSB strategies, promotes systematic investigations in which new understanding resulting from one mission provides the justification and impetus for further studies. Thus, a break in the logical progression of missions, whether due to cancellation or a failure of one sort or another, will usually require that the lost mission, or an improved version of it, be re flown. As a result, a fundamental assumption of this report is that certain ongoing or approved space missions will either be successfully implemented or will continue to operate as planned. In particular, in conducting this study, TGSAA made the following assumptions:

- **The Hubble Space Telescope (HST),** the first of NASA's Great Observatories, will continue to operate until at least 2005, and planned upgrades in instruments (including NICMOS, STIS, and ACS) will proceed as currently scheduled and will operate successfully. HST is a 2.4-meter optical, ultraviolet, and near-infrared (following the installation of NICMOS in February 1997) telescope operating in low Earth orbit.
- **The Compton Gamma-Ray Observatory (CGRO),** the second of NASA's Great Observatories, will operate at least until 2004. Although its high-energy gamma-ray telescope, EGRET, has ceased routine operations, three of the satellite's four instruments continue to provide the only gamma-ray observations from space, including the continuing study of the mysterious gamma-ray bursts.
- **The Advanced X-Ray Astrophysics Facility (AXAF),** the third of NASA's Great Observatories, will be launched according to schedule in late 1998 and will be operated for at least 5 years. AXAF is equipped with grazing-incidence mirrors and four scientific instruments designed to perform high-spatial-resolution imaging and spectroscopy in the 0.1- to 10-keV x-ray band.
- **The Far-Ultraviolet Spectroscopic Explorer (FUSE),** nominally the first of NASA's mid-size Explorer (Midex) spacecraft, will be launched according to schedule in late 1998 and will be operated for approximately 3 years. FUSE is designed to conduct high-resolution spectroscopic observations in the far-ultraviolet spectral band between 90 and 120 nm.

- **The Space Infrared Telescope Facility (SIRTF),** the fourth and final Great Observatory, will be launched according to schedule in 2001 and will operate for at least 2.5 years. SIRTF is equipped with a 0.85-meter cryogenically cooled mirror and three scientific instruments. It is designed to perform very sensitive photometric and imaging observations at wavelengths between 3 and 180 microns and spectroscopic observations in the band between 5 and 40 microns.
- **The Stratospheric Observatory for Infrared Astronomy (SOFIA)** will have its first flight in 2001 and will operate for approximately 20 years. SOFIA is a Boeing 747 aircraft modified to carry a 2.5-meter telescope to an altitude in excess of 12,000 meters on a routine basis. SOFIA will be equipped with a variety of instruments designed to operate in the optical, infrared, and submillimeter bands between 0.3 and 1,600 microns.

In addition, TGSAA assumed that the major ground-based facilities recommended by past decadal reports either would be completed or would continue to operate as they do currently. These facilities, together with other ground-based observatories such as the 10-meter Keck telescope and the instrumentation at the various national optical and radio astronomy observatories, are essential tools for the long-term study of objects discovered by space-based instrumentation. The complementary role of ground-based observatories is so important that any disruption in the operation of this important infrastructure could have serious, long-term consequences for the effective exploitation of space-based astronomical instruments. TGSAA also believes that laboratory and theoretical studies and instrument development are essential complements to the productive use of space-based research facilities.

RELATED CONCERNS

International Cooperation

Space science is a thoroughly international activity, with a growing number of nations now capable of independently mounting important astronomical missions. As budgets shrink, the possibility of leveraging scarce U.S. resources by encouraging international participation in NASA missions, or by flying U.S. instruments on foreign spacecraft, looks ever more promising. Such collaborative activities have many advantages beyond the better use of limited resources; these advantages include broadening the participation in the space-research endeavor and promoting communication between diverse elements of the worldwide astronomical community.

Although a consideration of the international aspects of space astronomy and astrophysics is technically outside its charge, TGSAA is aware that cooperative projects are increasingly necessary to implement the recommendations of the decadal surveys. A good example of this trend is NASA's plan to install the x-ray calorimeter originally designed to fly on the cancelled AXAF-S mission on Japan's forthcoming Astro-E x-ray astronomy satellite. Given current budgetary trends, some consideration of international cooperation is a necessary component of any space-science strategy.

Despite their many attractive features, cooperative activities can, however, have significant drawbacks. Although it is supportive of cooperative activities, TGSAA also believes that they must not be entered into lightly. Problems encountered during such activities can cancel all related benefits and have a chilling effect on future collaborations.

The following general principles, espoused in past SSB reports,[10] should be borne in mind when cooperative activities are being considered:

- Selection of foreign scientists and experiments for U.S. missions should be based on scientific merit, and the free flow of scientific data and results should be a condition for any cooperative arrangements;
- NASA should consider all appropriate foreign capabilities available for planning and carrying out its missions and should cultivate those that enhance the scientific return; and
- NASA should fully involve the scientific community in planning for international cooperation and in assessing proposed cooperative missions.

Technology Development

Another issue not specifically included in TGSAA's charge, but essential to the successful execution of any science strategy, is technology development. Future advances in space astronomy and astrophysics are very strongly tied to the development of new technology. Calling for significant investment in this area might appear obvious, but report after report has criticized NASA's lack of investment in technology.[11] Increased attention to new technology is now more important than ever before. In the past, much technology development has been funded as an integral part of major missions such as HST, AXAF, and SIRTF. Small missions with short development schedules—the type currently in favor at NASA—provide little or no opportunity for technological advance. With the end of the Cold War and the increasing availability of technology developed for military applications, NASA has an opportunity to substantially close this gap. Given TGSAA' s lack of in-depth expertise in many technological areas, additional studies by expert groups should be undertaken before some of the scientific priorities identified in this report are implemented as missions.

ORGANIZATION OF THIS REPORT

To set overall scientific priorities from among the broad range of topics in space astronomy and astrophysics, TGSAA organized itself into four panels, each dealing with a number of closely related fields of research, along the following lines:

- *Planets, star formation and the interstellar medium*, including the search for extrasolar planets, how stars and planets form, and the evolution of the interstellar medium in galaxies (Chapter 2);
- *Stars and stellar evolution*, including the life cycles of stars, the origin of the chemical elements, and the use of stars as celestial laboratories (Chapter 3);
- *Galaxies and stellar systems*, including the formation and evolution of galaxies, exotic processes in galactic nuclei, the intergalactic medium, and the large-scale structure of the universe (Chapter 4); and
- *Cosmology and fundamental physics*, including the cosmic microwave background radiation, large-scale structure of the universe, gravitational astronomy, and cosmic mysteries such as gamma-ray bursts and ultrahigh-energy cosmic rays (Chapter 5).

Not surprisingly, certain topics do not fall neatly within these categories and could, with equal justification, be included in several different chapters. Pre-main sequence stars, for example, can be considered as the end points of star formation or the starting point of stellar evolution. Similarly, gamma-ray bursts could be discussed in the context of a stellar or a cosmological phenomenon. In the interest of brevity and to avoid redundancy between different chapters, several somewhat arbitrary assignments have been made. Gamma-ray bursts, for example, are still such a mystery that all discussion of them can be found in the section titled "New Astrophysical Windows and Cosmic Mysteries" in Chapter 5. On the other hand, topics such as large-scale structure and dark matter have clearly defined aspects that fit naturally within different parts of the text. Thus the linear and nonlinear aspects of large-scale structure are discussed in Chapter 5 and 4, respectively. Similarly, the role played by dark matter in the structure and evolution of the universe is found in Chapter 5, while its influence on galaxies and clusters of galaxies is discussed in Chapter 4.

In general, each of the chapters devoted to the four principal topics (Chapters 2 through 5) follows a similar format. Each begins by defining a number of topical themes (e.g., dark matter, origin of the elements, and so on) around which the remainder of the chapter is organized. The text devoted to each theme begins with introductory material and is followed by a listing of key questions for which answers are needed to advance current understanding. The discussion of each theme then continues by describing recent progress in relevant studies and ends with a review of thematic priorities outlining suggested future directions for investigation. Each chapter concludes with a summary of the most important discipline-oriented scientific priorities as distilled from each thematic section.

The key questions and various priorities outlined in each chapter serve a number of parallel roles:

1. First and foremost they serve as a mechanism by which the diversity of topics found in each chapter could be distilled to a sufficient level that it was possible for each panel to devise a rank ordering between a manageable number of roughly comparable activities. The detailed discussion of the final priorities in each of the Chapters 2 through 5 then constitutes the foundation on which the priorities described in Chapter 6 were constructed. This final step, the selection of a series of overall priorities for the major aspects of NASA's future programs in space astronomy and astrophysics, was performed by TGSAA's steering group following debate, discussion, and a series of ballots. The steering group's final rank ordering was subsequently ratified in the same way at a joint meeting between TGSAA's steering group and the Committee on Astronomy and Astrophysics.
2. They demonstrate the depth and diversity of current activities in space astronomy and astrophysics and their potential for future advances on a broad front. As such they are an advertisement for the richness of opportunities open to enterprising researchers.
3. They provide a measure of justification and support to principal investigators proposing Midex and other small missions, and, conversely, guidance to peer-review panels selecting such missions. With NASA's deemphasis of large missions, the Explorer program and other small-mission lines have assumed a new significance as a means by which priority topics in space astronomy and astrophysics are addressed. Past decadal surveys have not, however, provided much strategic guidance on the conduct of such missions.

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2

Planets, Star Formation, and the Interstellar Medium

Understanding the formation of stars and planets has long been a major astronomical goal, and important progress has been made in the recent past. The most important development is the detection of planets around normal, nearby stars. These planets, with masses ranging from a few tenths to a few times that of Jupiter, were detected by the small wobble they produce in the motion of their parent stars. in addition, the first substellar object—the companion to the nearby star GL 229—has been imaged, and its spectral characteristics have been identified as being similar to that of a giant planet. The detection of extrasolar planets represents the culmination of more than two centuries of speculation and observation that began with the hypothesis of Laplace and Kant that a rotating gas cloud would collapse into a flattened disk to form a star and an associated planetary system.

Another important development has been the ability to observe directly the protostellar disks out of which planets appear to form. Such observations have shown that the formation of stars and protostellar disks begins in our galaxy's tenuous interstellar medium. Much has also been learned about the structure of the interstellar medium and how it affects and is affected by star formation.

The same process of star formation observed in the Milky Way is seen in other galaxies as well and is a crucial factor in their formation and evolution. However, astronomers' knowledge is very fragmentary at present; it is not yet possible to predict how the environment of a galaxy affects its interstellar medium and star formation, how the elements created within stars are dispersed into the interstellar medium, the rate at which stars form, what types of stars will form, the nature of the planetary systems that will result, or whether the planetary systems will be hospitable to life.

KEY THEMES

The fundamental scientific goal in studies of star formation and the interstellar medium is to understand how stars and planets form and how habitable environments might arise from the evolving interstellar medium in galaxies. This goal can be subdivided into three themes that link the formation of planets like Earth to the formation and evolution of galaxies:

- Formation and evolution of planetary systems;
- Formation of stars from the interstellar medium; and
- Evolution of the interstellar medium in galaxies.

FORMATION AND EVOLUTION OF PLANETARY SYSTEMS

The recent discovery of extrasolar planets is enormously exciting to the general public. It is also of great scientific interest, since we now have within our grasp the ability to answer age-old questions about the formation and evolution of planetary systems, the existence of nearby solar systems, and the possibility that there are other habitable planets in the universe. The study of such planets represents an entirely new field of astronomy that will almost certainly experience explosive development in the coming decade. There are two complementary approaches to this subject. One is inferential: researchers can study the process of star formation so as to understand the physical conditions in which planets form as part of the birthing process of stars like the Sun. The second is more immediate and involves searching for planets themselves via a host of techniques that are just now being perfected. These techniques range from the study of perturbations to the velocity, position, or brightness of parent stars, to the detection and spectral analysis of light from the planets themselves.

Key Questions About the Formation and Evolution of Planets

Important questions about the formation and evolution of planets include the following:

Frequency of Occurrence and Physical Characteristics

- How many planets are there around the nearest 1,000 stars, and what are their masses and distances from their parent stars?
- How do the properties of planetary systems vary with stellar type, age, and metallicity?
- How does the incidence of planetary systems depend on stellar multiplicity?
- What is the frequency of terrestrial planets?

Suitability for Life

- What are the atmospheric temperatures, densities, and chemical compositions of extrasolar planets?
- How do these conditions depend on a planet's distance from its parent star?
- Are possible signatures of a habitable planet, such as H_2O, O_2, or O_3, present?

Evolution of Disks and Formation of Planets

- What is the initial star/disk mass ratio, and how does this ratio evolve with time?
- When and how do planets form in a disk?
- How does planet formation depend on the mass of the planet?
- How does the formation of planets affect the evolution of the disk?
- How does planet formation depend on the number of stars in the system?

Evolution and Stability of Planetary Systems

- How long are planetary systems stable?
- How does the stability of a planetary system depend on the masses of its constituents?
- How did the solar system's Kuiper Belt originate, and what is its relationship to planetary debris disks?

Recent Progress in Understanding the Formation and Evolution of Planetary Systems

The past 2 years have seen the culmination of a decades-long search for planets around normal, nearby stars. Nearly one dozen stars are now known to have planets with masses ranging from a few tenths to a few times the mass of Jupiter and with orbits at distances ranging from a few hundredths of an astronomical unit to a few astronomical units from their parent stars. They were detected through very precise measurements of the radial velocity or positions of their parent stars. With current techniques, many more planets, some as small as Saturn or even Uranus, will probably be discovered by ground-based telescopes over the next decade.

Along with indirect detection of planets, direct detection of light from a planet-like object outside the solar system has been achieved for the first time. The "brown dwarf" or "super-Jupiter," GL 229B, lies about 7 arc sec (˜50 AU) from its parent star; its spectral energy distribution implies a temperature of ˜1,000 K, and its spectrum in the near infrared is dominated by methane absorption like that seen in the spectra of gas-giant planets in the solar system. The luminosity and temperature of GL 229B, coupled with theoretical models, suggest a mass roughly 50 times that of Jupiter.

The formation of planets around normal stars appears to be intimately tied to the formation of the stars themselves. Millimeter interferometers have resolved a few disks around nearby T Tauri stars, revealing gas in Keplerian orbits, but the best angular resolution now attainable with visible and infrared telescopes and millimeter interferometers can barely resolve them. Current understanding of planet-forming disks is limited to crude estimates of their size (less than a few hundred astronomical units), mass (a few tenths of a solar mass), and lifetime (less than a few million years).

Future Directions for Understanding the Formation and Evolution of Planetary Systems

To achieve an understanding of the formation and evolution of other planetary systems, it is essential to develop a capability for making infrared observations of unprecedented sensitivity, dynamic range, and angular resolution—a long-range goal beyond the time horizon of the scientific goals considered by TGSAA. Nonetheless, development should commence on the technology that will enable both infrared spectroscopy of terrestrial planets within 10 parsecs (pc) of the Sun and mapping of protostellar disks within about 150 pc of the Sun at sufficient resolution to clearly resolve both the inner disk (˜0.1-AU resolution at 5 to 10 μm) and the outer disk (˜1-AU resolution at 50 to 100 μm).

For the coming decade, the most important future directions identified by TGSAA for the study of extrasolar planets are, in priority order, as follows:

1. **Performing a census of planetary systems around nearby stars**. This sample should include enough stars (˜1,000) so that the frequency, separations, and masses of planets can be investigated as functions of the most important parameters, specifically stellar mass, multiplicity, metallicity, and age. Precision astrometry is a critical part of the goal of obtaining a census of nearby planets; for the 1,000 nearest stars, observations with an accuracy of 5 to 10 microarc sec are required to detect planets with a mass similar to that of Uranus and with an orbit a few astronomical units in radius. The required duration of the census-taking mission depends on the orbital periods of the planets and the complexity of the planetary systems, but a decade (comparable to the orbital period of Jupiter) seems reasonable.
2. **Detecting extrasolar terrestrial planets**. It is preferable to attempt detection of extrasolar terrestrial planets around nearby stars by astrometry at the 1-microarc sec level, so that follow-up observations can be made of the planets and their associated planetary systems. However, observations of more distant planets, by photometry or gravitational microlensing, might provide statistical evidence regarding the frequency of occurrence of terrestrial planets.
3. **Imaging protostellar disks with 10-milliarc sec resolution**. In nearby star-forming regions, imaging at 10-milliarc sec would reveal features as small as 1 AU and would permit direct observation of the disk-stellar wind interface region, gaps in disks owing to the presence of planets, and hot, young protoplanets.
4. **Obtaining images and spectra of gas-giant planets around nearby stars**. Crude spectroscopy (R˜100) would enable characterization of the atmospheres of these objects. Such planets might be detected in reflected starlight or, if they are massive, as self-luminous infrared objects.

Ground- vs. Space-Based Observations

The critical capability for obtaining the desired census of planets is astrometry with a positional accuracy of ≤10-microarc sec. Although ground-based astrometry will play an important role, particularly in detecting large planets on long-period orbits, space-based observations offer the greatest potential for finding planets of low or moderate mass. Similarly, direct imaging of large planets close to their parent stars could be accomplished by means of a space-based interferometer with a 10- to 20-meter baseline; low-resolution spectroscopy of such planets could be done with a high-dynamic-range coronagraph on a space-based telescope.

Ground-based observations will also contribute to attaining these goals. Both radial velocity measurements and astrometry can contribute to obtaining a census of extrasolar planets. The amplitude of the stellar radial velocity induced by a planet depends on the angle of inclination of the orbit, which is unknown; it decreases with the size of the orbit, so that the radial velocity technique is most sensitive to planets close to their parent star. Astrometric observations are complementary to studies of radial velocities: they are independent of the angle of inclination and therefore provide unambiguous measurements of planetary masses, and they are most sensitive to planets far from their parent star. Although space-based observations still appear to offer the greatest accuracy, particularly over wide angles, substantial improvements in ground-based astrometry are possible.

Terrestrial planets might also be detectable through gravitational microlensing; surveys of 30 million to 50 million stars toward the galactic bulge should result in the observation of ˜100 lensing systems per night, and careful monitoring of these systems might find the small increase in brightness over the nominal microlensing signal induced by a planet in the lensing zone. High-resolution imaging of protostellar disks in the mid- and near-infrared should be possible if the two Keck telescopes are equipped with outrigger elements. Finally, advanced adaptive optics on large ground-based telescopes offer the possibility of obtaining low-resolution spectra of a few tens of planets of jovian-mass around the nearest stars.

Theoretical Studies

Theory is important for all of space astronomy and astrophysics and will continue to play a leading role in guiding and interpreting observations of extrasolar planets. Theory is particularly important in the study of the stability of planetary systems. The recent detections suggest that planetary systems may be not only ubiquitous, but also remarkably diverse. For example, the planet orbiting 51 Pegasi is as massive as Jupiter but is as close to its star as Mercury is to the Sun. Did it form that close to 51 Pegasi, or is it the product of unstable long-term evolution? Theoretical analyses indicate that the solar system itself is marginally unstable. The long-term dynamical evolution of planetary systems may also account for the debris disks observed around 15 to 20% of main sequence A-K stars, and for the formation and evolution of the Kuiper Belt in the solar system.

FORMATION OF STARS FROM THE INTERSTELLAR MEDIUM

Knowledge of how stars form is critical to understanding both the origin and evolution of systems of stars, such as galaxies, and the origin and evolution of planetary systems. Although star formation is an ongoing process in the Milky Way, observing the creation of stars from interstellar material has proved to be a formidable challenge for astronomers. Stars are born deep within the cold, dust-enshrouded cores of dark molecular clouds where the opaque dust renders newly forming stars invisible to even the most powerful optical telescopes on the ground and in space. However, it is possible to penetrate the veil of obscuring dust with observations in the infrared, submillimeter, and millimeter wavelength bands of the spectrum. Unfortunately, Earth's atmosphere is itself opaque over a large portion of this wavelength range, making such long-wavelength observations difficult or impossible from the ground. The direct investigation of star formation is therefore a recent development of astronomical science, which has required both space-based and ground-based observational facilities at the forefront of technological capabilities.

Over the last 20 years, great progress has been made toward understanding how stars form. Major milestones include discovery of the following:

- Giant molecular clouds, the largest, most massive, and coldest objects in our galaxy, and the sites of all present star formation;
- Bipolar molecular outflows, very energetic jets of cold molecular gas that appear to be a natural by-product of the formation of all stars; and
- Circumstellar disks surrounding young stellar objects, which are believed to be the sites of planet formation.

Astronomers' current understanding suggests that the gravitational collapse of a dense cloud core is the basic mechanism by which stars are formed, but the most fundamental aspects of how this happens remain unknown. Observers still have not achieved an unambiguous identification of a protostellar object.

Key Questions About Star Formation

Important questions about the formation of stars from the interstellar medium include the following:

Core Collapse

- What are the properties of protostellar cores in giant molecular clouds?
- How do the cores affect the kind of star and planetary system that emerge from the collapse process?
- What are the properties of infalling protostellar material over the range of scales from 0.1 to 1,000 AU?
- What are the size and mass distributions of protostellar disks, and how are they related to protostellar luminosities and evolutionary states?
- How luminous are protostellar objects, and how does their luminosity evolve with time?

Role of Clusters

- Do neighboring young stars have an important influence on the formation of a protostar?
- Do neighboring stars play an important role in determining the spectrum of initial stellar masses or the rate of star formation?
- How do the conditions in protoclusters affect the survivability of circumstellar disks?
- How do supernovae and spiral density waves influence star formation?

Masses of Stars

- What factors determine the mass of an individual star?

Bipolar Flows

- What is the origin of bipolar outflows, and what is their role in star formation?
- How do bipolar outflows change the structure of the ambient molecular cloud?

Molecular Clouds and the Interstellar Medium

- How do molecular clouds evolve to form dense cores?
- What is the physical and chemical structure of a giant molecular cloud?
- How do giant molecular clouds evolve, and do they have a well-defined age?
- What is the mass spectrum of dense cores, and what determines it?
- How do magnetic fields and turbulence influence the structure and evolution of molecular clouds?
- How does star formation within a cloud influence the cloud's structure?
- How does the rate of star formation depend on the properties of the ambient medium?

Recent Progress in Understanding Star Formation

Spectroscopic observations at millimeter wavelengths recently provided evidence for protostars with infalling material. Three such sources have now been identified, and these are among the coldest and most deeply embedded young stellar objects known.

Millimeter-wave interferometry has produced the first resolved images of disk-shaped structures around protostellar objects. These observations have also provided spectroscopic detection of disk rotation, confirming the nature of these objects as circumstellar disks. With the detection of disk rotation around a number of young stellar objects, near-infrared spectroscopy has provided additional evidence for circumstellar disks. Hubble Space Telescope (HST) observations have also detected disks and gaseous globules around low-mass stars in regions of massive star formation, providing a new approach to the study of such disks (Figure 2.1).

Deep-infrared imaging of giant molecular clouds has revealed that star formation occurs exclusively in dense molecular cores and that a significant, and perhaps dominant, fraction of all stars form in rich Stellar clusters generally embedded in the most massive molecular cores. These observations have also suggested that the outcome of such star formation is an initial spectrum of stellar masses that is universal in form and similar to that of field stars in the neighborhood of the Sun.

Millimeter-wave, optical, and infrared imaging have established a close relationship between optical jets and molecular outflows, indicating that these two types of flows have a common physical origin. HST observations have resolved optical jets and have revealed that they become collimated very close to the star, on scales comparable to the size of the solar system. Millimeter, submillimeter, and far-infrared observations have established that the most collimated and energetic bipolar outflows are closely linked with the most embedded and least evolved young stellar objects, suggesting that the most active outflow phase occurs simultaneously with the most active infall phase of protostellar evolution.

Future Directions for Understanding Star Formation

Improved angular resolution and sensitivity at infrared and submillimeter wavelengths are essential to future progress in all areas of star formation research. High-resolution imaging and spectroscopy of the disks, jets, and inner envelopes of the nearest protostellar systems are particularly important. Because such a capability is crucial for understanding star formation as well as planet formation, the development of space-based infrared interferometry to achieve the capability should be emphasized.

In the near term, three scientific goals—given below in priority order—can be addressed within technological capabilities existing now and projected during the next decade:

1. **Characterizing the very earliest stages of star formation by observing the structure and dynamics of protostellar regions**. High-resolution far-infrared and submillimeter spectroscopy at a velocity resolution of 0.3 km/s or better will enable the study of collapsing regions of dense cores on scales between 100 and 1,000 AU in spectral lines that are blocked by Earth' s atmosphere. Spectroscopic observations of strong cooling lines from OH and H_2O in the 50- to 350-μm band could enable the first identification and study of protostellar disk accretion shocks and of the cooling regions of molecular outflows. Observations of protostars in the 100- to 800-μm band could provide accurate determinations of protostellar luminosities and the protostellar luminosity function, thereby directly testing and refining predictions of star formation theory. Surveys in the 150- to 350-μm band could provide a complete inventory of protostellar activity in all nearby molecular clouds.
2. **Determining the luminosity functions of embedded stellar populations over a range of differing environments**. The best techniques to achieve this goal are high-resolution (0.1-arc sec), near-infrared (2- to 5-μm) imaging, and modest-resolution spectroscopy (R~3,000) of young embedded star clusters within 5 kpc of the Sun. Such observations will test the universality of the initial stellar mass spectrum, particularly in regions where high-mass stars form, and they will determine the rate of star formation as a function of physical environment and location in the galaxy.
3. **Measuring the frequency, separations, and orbital motions of binary companions of protostars on**

scales of 0.5 to 5 AU. Observations of the orbital motions of protostellar binaries would give the first determinations of protostellar masses, measurements fundamental to the development of a theory of protostellar evolution. In addition, knowledge of the frequency of companions is vital to understanding the process of fragmentation in star formation and the survivability of protoplanetary disks.

Although space-based observations are required to attain most of these objectives, it is possible to achieve a major scientific goal of star formation studies from the ground: of particular importance are imaging and spectroscopy of nearby protostellar regions at extremely high angular (10-milliarc sec) and spectroscopic ($R \sim 10^6$) resolution at 350-μm wavelength. Such observations will enable resolved imaging of protostellar disks and inner envelopes in the nearest star-forming regions. This goal could be achieved with a ground-based interferometer array operating at 350 μm at a high-altitude site with a minimum baseline of at least 15 km.

EVOLUTION OF THE INTERSTELLAR MEDIUM IN GALAXIES

The evolution of the interstellar medium in galaxies is central to galactic structure and star formation on a galactic scale. Astronomers wish to understand the processes that control the efficiency of star formation and the nature of the stars that form. On larger scales they need to understand the rate and extent of the dispersal of hot gas, ionizing photons, and nucleosynthetic products throughout the galactic disk and halo. Most generally, investigations of the interstellar medium of galaxies may answer fundamental questions such as the following: What triggers star formation in a galaxy? What determines how star formation propagates and evolves in time? What is the feedback of star formation on the interstellar medium? What are the key extragalactic environmental effects on galaxy evolution?

The birth sites of new stars are the giant molecular clouds (GMCs), which together occupy a small fraction of the volume of a galaxy but contain substantial mass (several times 10^9 solar masses). A typical (10^5 to 10^6 solar masses) GMC is probably built by assembling diffuse atomic clouds from a volume extending hundreds of parsecs on a side. These diffuse clouds are heated primarily by the interstellar ultraviolet radiation field and are cooled primarily by [C II] (158 μm). The formation of a GMC from diffuse clouds may be accompanied by shocks that emit copious [C II] (158-μm) and [O I] (63-μm) radiation.

One of the greatest obstacles to understanding the cycles of star formation and galactic evolution is a lack of knowledge about the distribution on all scales of the material composing the diffuse interstellar medium. This information is critical for understanding key aspects of star formation, such as its efficiency, the energy dissipated, and the mechanisms that trigger it and shut it off. The Sun resides in a "local hot bubble"; over much of the volume within 100 pc, the density of interstellar matter is less than 1% of the mean interstellar value, and the temperature is extremely high: greater than 10^6 K. Astronomers do not know whether such low-density gas occupies 10% or 80% of the disk, nor do they know its structure and topology or those of the denser gas that surrounds it. Even locally, astronomers have no consistent model for the location of the million-degree gas that produces the very bright, 0.25-keV x-ray background. These factors can be central in determining the mechanisms that eventually control star formation and galactic evolution. Attempts to observe the spectrum of this hot gas have been frustrated by the low spectral resolution available, so that astronomers do not understand the physical conditions in the hot gas. Observations of 0.5- to 1-keV x rays suggest that there is a large amount of even hotter gas at several million degrees in the inner galaxy, which may drive a strong outward wind.

At the outer limits of a galaxy, the gaseous galactic halo is an equally dynamic but poorly understood entity. The halo acts as a reservoir for the stellar and gaseous debris blown out of the disk, and for the cosmic rays that diffuse out. Galactic halos may also be replenished by the infall of gas from the intergalactic medium; observations of quasar absorption lines suggest that galactic halos exist at high redshift and show evidence for massive-star nucleosynthesis. The origin, structure, and evolution of these halos are not understood.

Key Questions About the Evolution of the Interstellar Medium

Major unresolved issues concerning the evolution of the interstellar medium in galaxies include those listed below:

Formation of Molecular Clouds

- What are the relative roles of gravitational and thermal instabilities, magnetic fields, and spiral density waves in the formation of GMCs?
- What determines the relative amounts and spatial distribution of atomic and molecular gas in galaxies?

Physical Properties of the Diffuse Interstellar Medium

- What are the physical properties of the different phases of the interstellar gas: the cold and warm neutral media, the warm ionized medium, and the hot ionized medium?
- What is the spatial distribution of these components within the galaxy, on both the scale of clouds and the much larger scale of spiral arms?
- What is the composition of interstellar dust, and what is the size distribution of its grains?
- What is the ionization source for the warm ionized medium?
- How do radiative losses and thermal conduction regulate the temperature of the hot gas?
- How are cosmic rays accelerated?

Interstellar Medium and Galaxies

- How is star formation organized in galaxies?
- What are the physical mechanisms that regulate the rate of star formation in galaxies?
- What is the role of supernova remnants in determining the structure of the interstellar medium?
- How are the nucleosynthetic products from supernovae and evolved stars mixed into the interstellar medium?
- What causes starbursts?
- How do globular clusters form?

Galaxies and Their Environment

- Are gaseous galactic halos the relics of galaxy formation or the products of violent events within galaxies?
- How does gas from the nucleus and disk of galaxies mix into the halo?
- galaxies and the intergalactic medium?

Recent Progress in Understanding the Evolution of the Interstellar Medium

Significant advances in our knowledge of the diffuse interstellar medium during the past 5 years have come from a number of space-science missions, including the International Ultraviolet Explorer (IUE), Infrared Astronomical Satellite (IRAS), Cosmic Background Explorer (COBE), Roentgensatellit (ROSAT), Extreme Ultraviolet Explorer (EUVE), Kuiper Airborne Observatory (KAO), Infrared Space Observatory (ISO), and HST. Many of these studies have focused on the physical properties of the diffuse interstellar medium. The far-infrared imaging of the galaxy by IRAS has highlighted previously invisible regions, both the portions of dark clouds heated by star formation and the diffuse "infrared cirrus" ubiquitous throughout the disk and halo. IRAS has also clarified the importance of dust re-radiation Of starlight, in which small particles absorb ultraviolet and optical starlight and reemit it at mid- and far-infrared wavelengths. COBE images have tantalized us with coarse maps of the [C II]

(158-μm) and [N II] (205-μm) emission lines, which trace the gaseous energy budget and the warm ionized medium, respectively. Similarly, mid-infrared spectroscopy from ISO shows the great value of measuring astrophysical conditions in diffuse atomic and molecular gas.

Probes of the hot gas in the local interstellar medium have been provided by ROSAT, which measures soft x-ray emission from gas at 10^6 to 10^7 K. ROSAT has also observed "x-ray shadowing," in which a foreground interstellar cloud absorbs x rays emitted by distant hot gas. Such observations provide estimates of the temperature, pressure, and structure of the hottest regions of the interstellar medium. Images and spectra from the KAO have enriched current knowledge of star-forming regions, supernovae, and galaxies in the far infrared. In addition to probing the coolest regions of the interstellar medium, mid- and far-infrared observations allow astronomers to study the reprocessing of starlight by dust grains and abundances of ionized nebulae from fine-structure lines.

Spectroscopic observations by the IUE and the HST have provided high-precision gas-phase elemental abundances for a range of interstellar environments, including gas in the local medium, the galactic disk, and distant halo clouds. These studies have yielded new information about the composition of interstellar dust, the origin of the galactic high-velocity clouds, and the processes that transport gas between the galactic disk and halo. EUVE has provided valuable information on helium in the local medium. HST images of gaseous matter in star-forming regions have also revealed the complex interactions between stars and their surrounding environments, beautifully shown in the giant pillars of gas and dust in the Eagle nebula (Figure 2.2).

Future Directions in Understanding the Evolution of the Interstellar Medium

Tackling the fundamental questions about the evolution of the interstellar medium in galaxies requires observational capabilities in space ranging from ultraviolet and x rays to the far infrared. In this section, TGSAA discusses specific scientific initiatives that would provide answers to many of the important questions discussed above by probing diffuse gas over the wide range of temperatures (10 to 10^7 K) present in the interstellar medium. Although optical instruments are sensitive to ionized nebulae at 10^4 K, observers require spaceborne, infrared and submillimeter instruments to study cool gas (10 to 100 K), ultraviolet spectrographs to study the resonance lines that trace the atomic and ionized gas (10^2 to 10^6 K), and x-ray spectrographs to observe the hottest components ($\geq 10^6$ K). Since observations of the interstellar medium in other galaxies can address many of the same scientific questions, most of these instruments can be used to study nearby galaxies as well. The most important future directions identified by TGSAA for research in this area over the next decade—in priority order—are as follows:

1. **Determining the large-scale three-dimensional structure of the interstellar medium**. Spectroscopy of the [C II] (158-μm), [O I] (63-μm), [N II] (205- and 122-μm), and (of lower priority) H_2 (28-, 17-, 12-μm) infrared emission lines at high spectral resolution ($\leq$10 km/s) and moderate angular resolution (<30 arc min) are particularly important. These lines trace the energy budget, the warm ionized and neutral medium, and warm molecular gas throughout the disk and halo. Not only would a [C II] and [O I] survey locate the diffuse clouds in the galaxy, but comparison with H I (21-cm) surveys and infrared continuum surveys would also reveal the density and temperature structure of the clouds. The mapping of [N II] will trace the leakage of ionizing photons from massive stars in the disk into the halo. The first two H_2 rotational lines at 28 μm ($J = 2 \rightarrow 0$) and 17 μm ($J = 3 \rightarrow 1$) will be observed primarily in photodissociation regions, the warm outer envelopes of GMCs illuminated by intense far-ultraviolet fluxes from regions of active star formation.
2. **Determining the connection between the Milky Way's disk and its gaseous halo**. High-resolution ultraviolet absorption-line spectroscopy of stars and quasars is the relevant technique to employ. Observations are needed of faint background targets at moderate resolution (15 km/s) and of brighter stars within 1 to 2 kpc at high resolution (1 km/s). In the long term, it is important to extend this capability down to 91.2 nm in order to measure key absorption lines of heavy elements, H_2, deuterium, O VI, C III, and S VI for a much wider variety of sources than will be possible with the Far-Ultraviolet Spectroscopic Explorer (FUSE).
3. **Mapping the soft x-ray background with a spectral resolution of 1 eV and, in stages, with an angular resolution approaching 1 degree** . Spectroscopy of the diffuse x-ray emission above 0.1 keV provides powerful diagnostics of the hot phase of the interstellar gas through the richness of its emission line spectrum. Understand

ing the distribution of this hot gas is central to determining its origin and its role in controlling the evolution of the interstellar medium and galactic halo.

4. **Mapping the spatial distribution of transition temperature gas (T ~ 1 to 3 × 10^5)** in the local disk and halo. This can best be achieved by mapping the ultraviolet emission lines of C IV (154.8 and 155.0 nm) and O VI (103.2 and 103.8 nm) at an angular resolution of 1 degree and a velocity resolution of 15 km/s. These emission lines are tracers of energetic processes in the interstellar medium.
5. **Mapping the physical conditions and composition of the hot gas in supernova remnants, superbubbles, and the galactic center**. This undertaking will require the development of high-throughput, high-resolution, x-ray spectroscopy. Large-scale maps can be obtained in prominent x-ray emission and absorption lines to measure the ionization and chemical composition of the hot gas. (The same techniques can be exploited to study young stars embedded in GMCs.) The spectral resolution should be adequate to study the dynamics of supernova remnants (velocity resolution of ~ 100 km/s).
6. **Mapping the coldest parts of the interstellar medium in selected atomic and molecular emission lines and in broadband thermal emission from dust grains**. This task will require the development of spectroscopy in the submillimeter and far-infrared bands.

CONCLUSIONS

For many years, astronomers have speculated that there should be planets around other stars, but only recently have extrasolar planets actually been detected. We now stand at the threshold of discovering both the nature of extrasolar planetary systems and how they came about. Are there other planetary systems such as the solar system, and if so, how did they form? The formation of planets is intimately tied to the formation of the stars they orbit; how do stars form? The formation of stars in turn is regulated by the structure of the interstellar medium; how does this medium evolve in the Milky Way and in other galaxies?

Answering these questions presents a major technological challenge owing to the enormous range of scales involved—from the size of galaxies to the size of planets—and the range of wavelengths over which observations must be made, from x rays for the hot gas in galactic disks to millimeter and submillimeter radiation for the cold gas and dust in protostellar disks.

The greatest gap in current knowledge is at the smallest scales, and motivates the long-term goals of developing systems that can obtain spectra of terrestrial planets around nearby stars and image protoplanetary disks in nearby star-forming regions. The first goal requires the ability to detect 5- to 20-μm radiation from a planet within 0.1 arc sec of a star that is over a million times brighter. Since the nearest star-forming regions are about 150 pc away, the second goal requires a resolution of about 1-milliarc sec at 5 to 10 μm to image the inner parts of the disk and about 10-milliarc sec at 50 to 100 μm to image the outer parts. In the long run, it will be essential to achieve these extremely challenging goals if we are to observe terrestrial planets around other stars and understand how they formed. Initiation of the technology development necessary to meet these long-term goals is of prime importance to the astronomical community.

Over the time scale considered by this report (the next ~10 years), the top three scientific priorities for the study of planets, star formation, and the interstellar medium are, in rank order, as follows:

1. **Obtain a census of planetary systems around enough stars (~1,000) so that the frequency, separations, and masses of planets comparable to or larger than Uranus can be investigated for a range of types of stars and stellar systems**. This activity will require complementary approaches of radial velocity measurements (better than 10 m/s) and high-precision astrometry (better than 10-microarc sec) over at least a 10-year period. Higher astrometric precision would allow the survey to be carried out to lower planetary masses and is clearly desirable.
2. **Characterize the very earliest stages of star formation by observing the structure and dynamics of protostellar regions**. Imaging and high-resolution spectroscopy in the far-infrared and submillimeter regions of the spectrum should reveal how the properties of the accreting gas, the circumstellar disks, and the molecular outflows depend on the evolutionary status and mass of the protostar.

3. **Determine the large-scale three-dimensional structure of the interstellar medium and the star-formation regions within it**. This project could be done by mapping the galaxy at high spectral resolution (<UN+>10km/s) and moderate angular resolution (<30 arc rain) in the infrared lines of [C II] (158 μm), [O I] (63 μm), IN II] (205 and 122 μm), and possibly H_2 (28, 17, and 12 μm).

At somewhat lower priority, TGSAA rated the following projects as of comparable importance for the next decade:

1. **Detect indirectly terrestrial-mass planets**;
2. **Perform ultraviolet spectroscopic studies of the connection between galactic disks and halos with a sensitivity significantly higher than that now provided by HST; and**
3. **Conduct near-infrared imaging and spectroscopic studies of young embedded star clusters**.

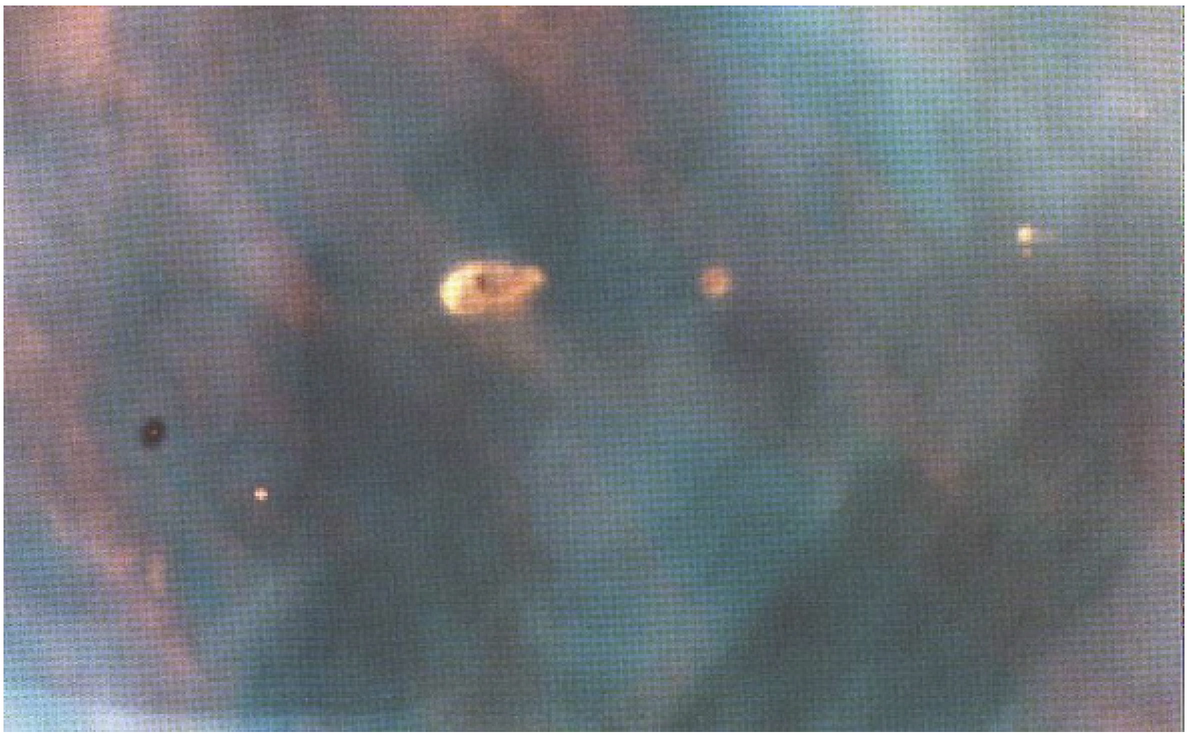

FIGURE 2.1
This small portion of the Orion nebula, a region of star formation approximately 1,500 light-years from Earth, contains five young stars, four of which appear to be surrounded by disks of gas and dust more than twice the diameter of the solar system. Such a disk is believed to have surrounded the young Sun and later to have given rise to Earth and the other planets. HST observations of these protoplanetary disks, or "proplyds," in Orion reinforce the assumption that planetary systems are common in the universe. This image was taken in December 1993 with HST's Wide-Field and Planetary Camera 2 and is provided courtesy of C.R. O'Dell and the Space Telescope Science Institute.

FIGURE 2.2
These columns of molecular hydrogen and dust are part of the Eagle nebula, an incubator for the birth of young, hot stars. The columns are slowly eroding due to the effect of ultraviolet light from nearby hot stars. As the erosion occurs, small globules of especially dense gas buried within the cloud are uncovered. These so-called evaporating gaseous globules protect gas behind them and give rise to the fingerlike structures. Inside some of the globules are embryonic stars—stars that abruptly stop growing when the globules are uncovered and they become separated from the larger reservoir of gas from which they are accreting mass. Eventually, the young stars emerge as the globules themselves succumb to photoevaporation. This image was taken in April 1995 by HST's Wide-Field and Planetary Camera 2 and is provided courtesy of Jeff Hester, Paul Scowen, and the Space Telescope Science Institute.

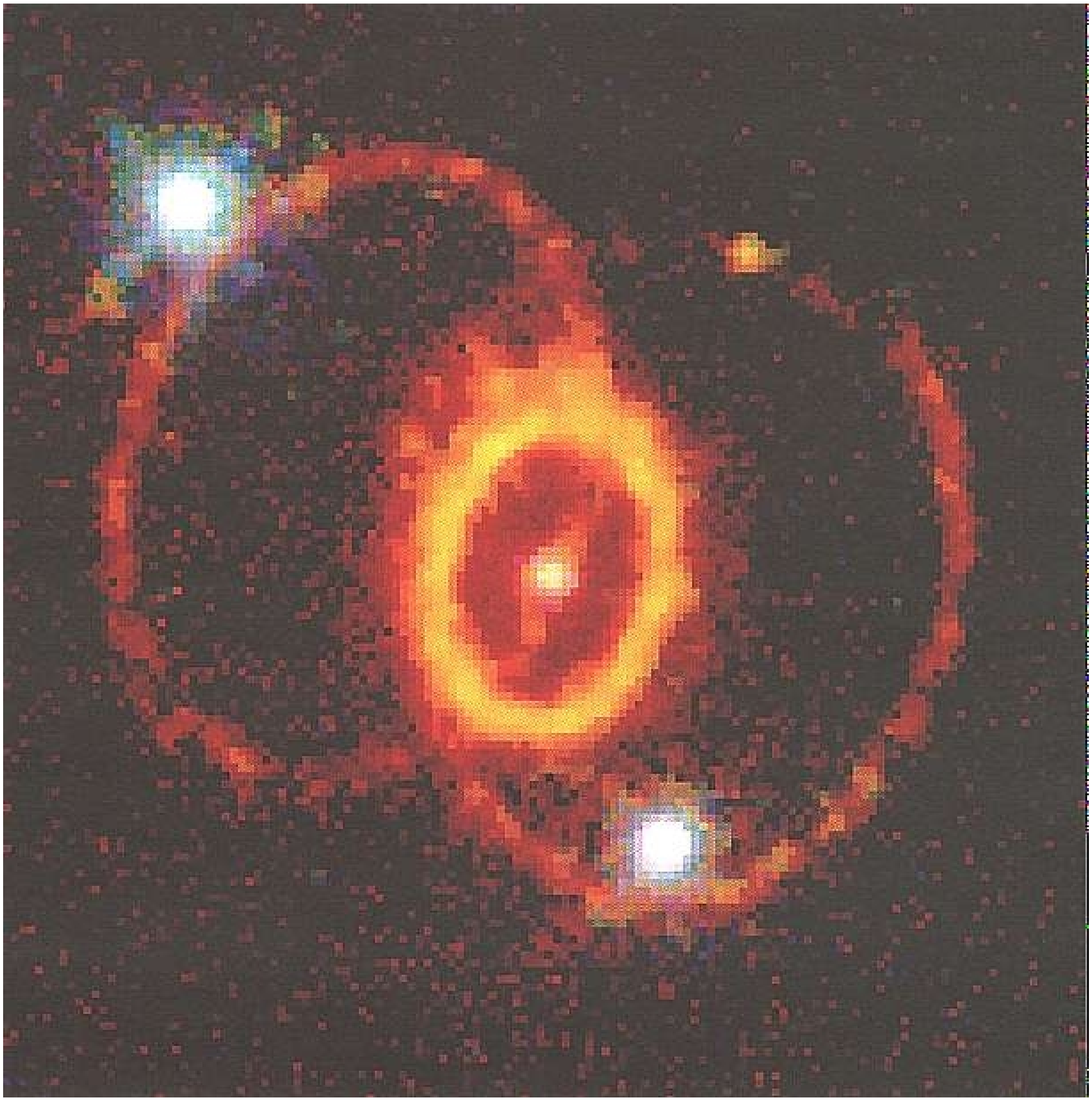

FIGURE 3.1
The complexity of stellar mass loss is illustrated by the three rings of glowing gas visible at the site of supernova 1987A. The appearance of the rings is something of a surprise because astronomers expected to see a bubble of gas created by interactions between a wind of slow-moving gas ejected when the supernova's progenitor star was a red supergiant and a fast-moving wind from the progenitor's subsequent blue supergiant phase. The nature and origin of the rings are currently under study. This image was obtained by HST's Wide-Field and Planetary Camera 2 and is provided courtesy of Christopher Burrows and the Space Telescope Science Institute.

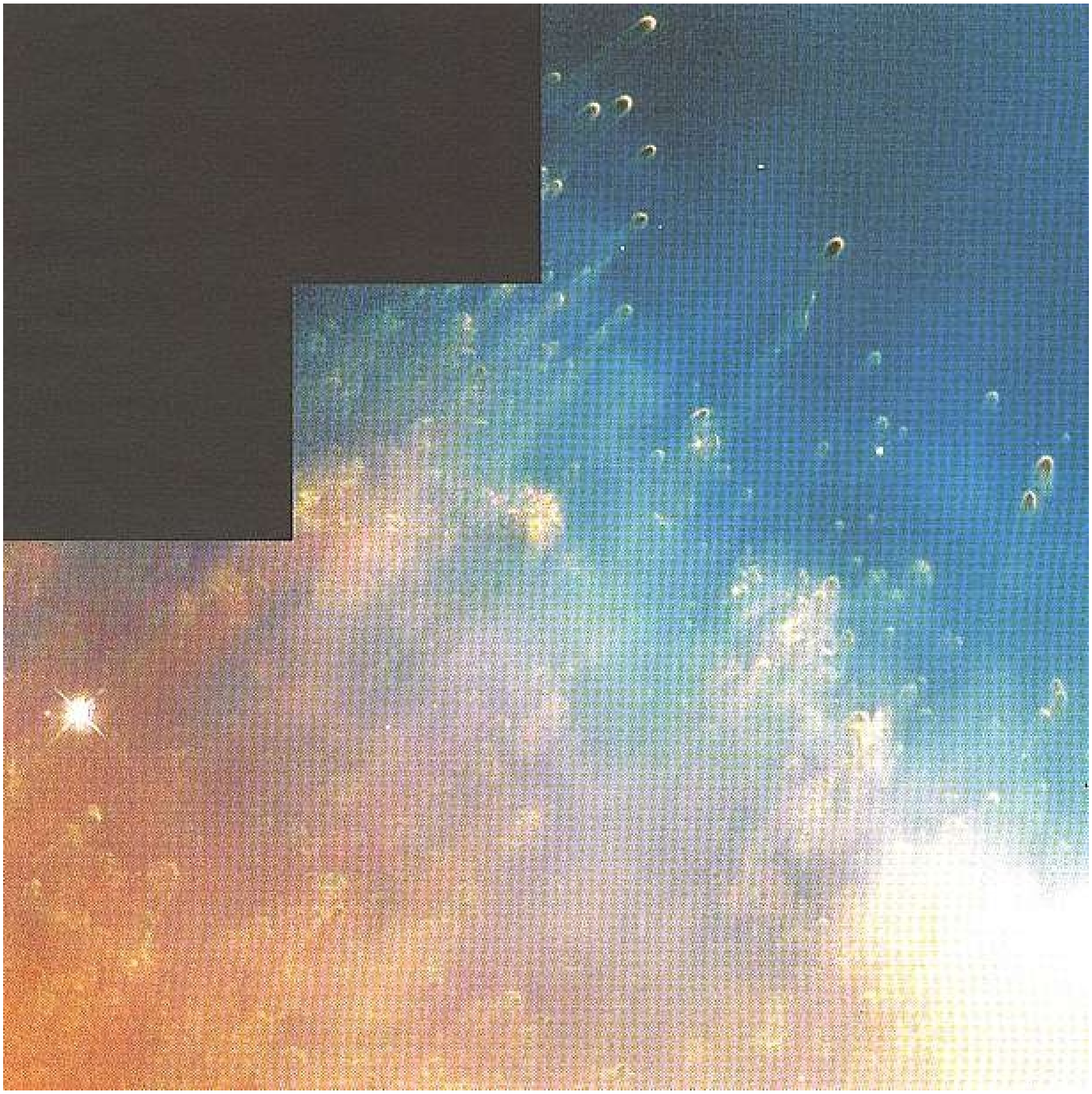

FIGURE 3.2
One manifestation of complex interactions between mass lost from stars in different stages of their evolution is clearly visible in this HST image of cometary knots in the Helix nebula, the planetary nebula closest to Earth. The head of each gaseous knot is approximately twice the size of the solar system, and the knots' long tails form a radial pattern around the star like spokes on a wheel. They are probably formed during the final years of a star's life when it ejects shells of gas into space. A faster-moving shell of hot, low-density gas collides with cooler, denser material released some 10,000 years earlier, and the resulting mixture fragments into smaller, denser, finger-like droplets. The resulting knots should expand and dissipate within a few hundred thousand years. This image was taken with HST's Wide-Field and Planetary Camera 2 in August 1994 and is provided courtesy of R. O'Dell, K.P. Handron, and the Space Telescope Science Institute.

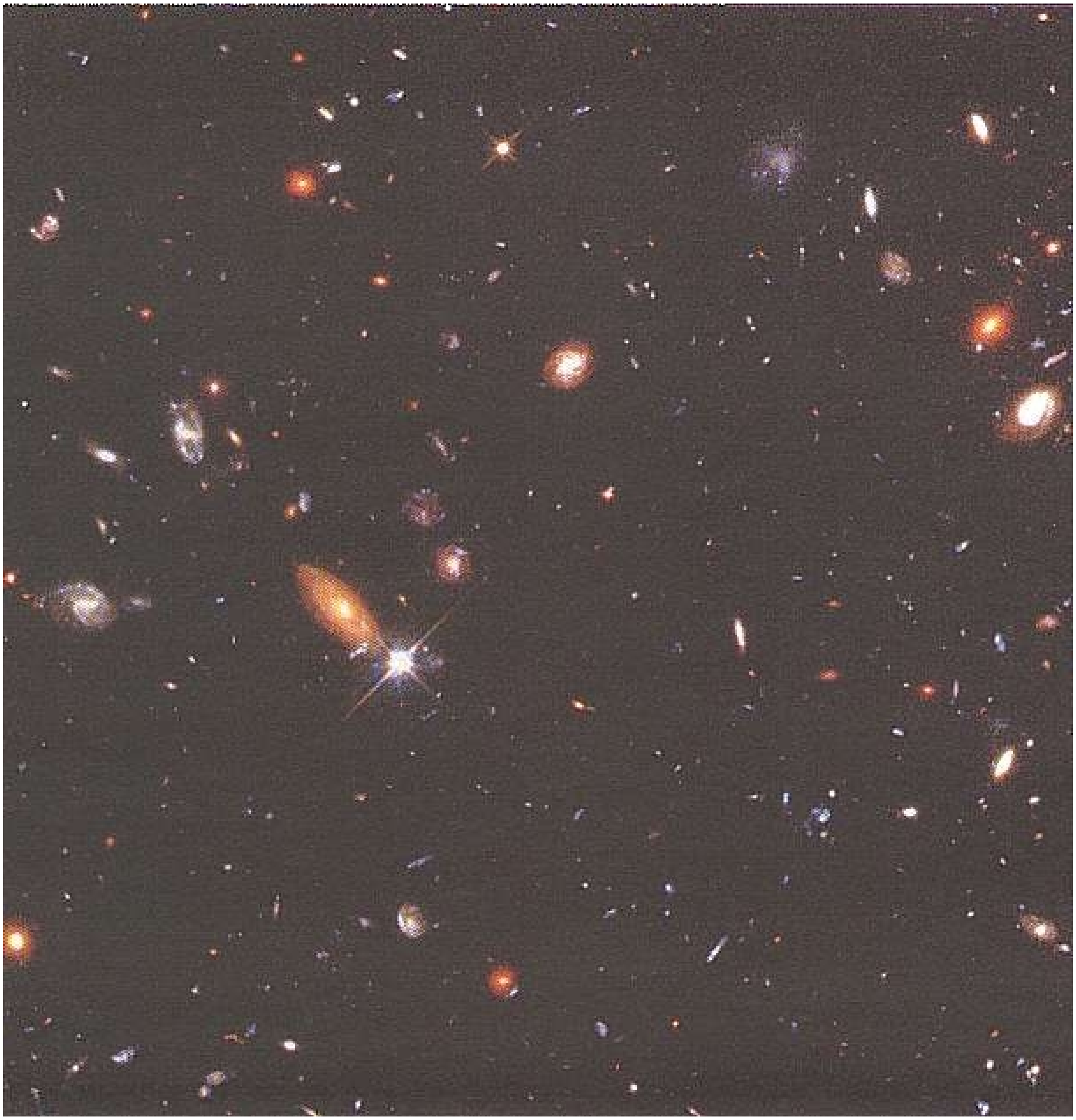

FIGURE 4.1
Some of the faintest, oldest, and most distant objects ever seen are visible in this HST image, a portion of the so-called Hubble Deep Field. This, the deepest image ever made of the universe, shows a bewildering variety of galaxies in virtually every evolutionary stage. The bright object just left of center is probably a 20th-magnitude star and the faintest galaxies shown are almost 30th magnitude. This region of sky, covering an area of only 1/30th the diameter of the full Moon, is located near the north galactic pole and was chosen because it is relatively uncluttered by objects within our own galaxy. Thus, it is a "keyhole" view of a typical part of the universe, containing a representative sample of galaxies some of which date back to within a billion years of the big bang. This image was compiled from 342 separate exposures of HST's Wide-Field and Planetary Camera 2 made between December 18-28, 1995, and is provided courtesy of Robert Williams and the Hubble Deep-Field Team at the Space Telescope Science Institute.

FIGURE 4.2
Gravitational lensing, the phenomenon by which light from a distant object is bent by the gravity of a massive intervening object, is clearly visible in this HST image of the cluster of galaxies 0024+1654. In this case, multiple lensing by a cluster of yellow spiral and elliptical galaxies has created five separate images of a distant, blue galaxy. These images are the blue arcs visible at the center of the cluster and surrounding it at the 2, 6, 7, and 8 o'clock positions. This image was taken on October 14, 1994, with HST's Wide-Field and Planetary Camera 2 and is provided courtesy W. Colley, E. Turner, J.A. Tyson, and the Space Telescope Science Institute.

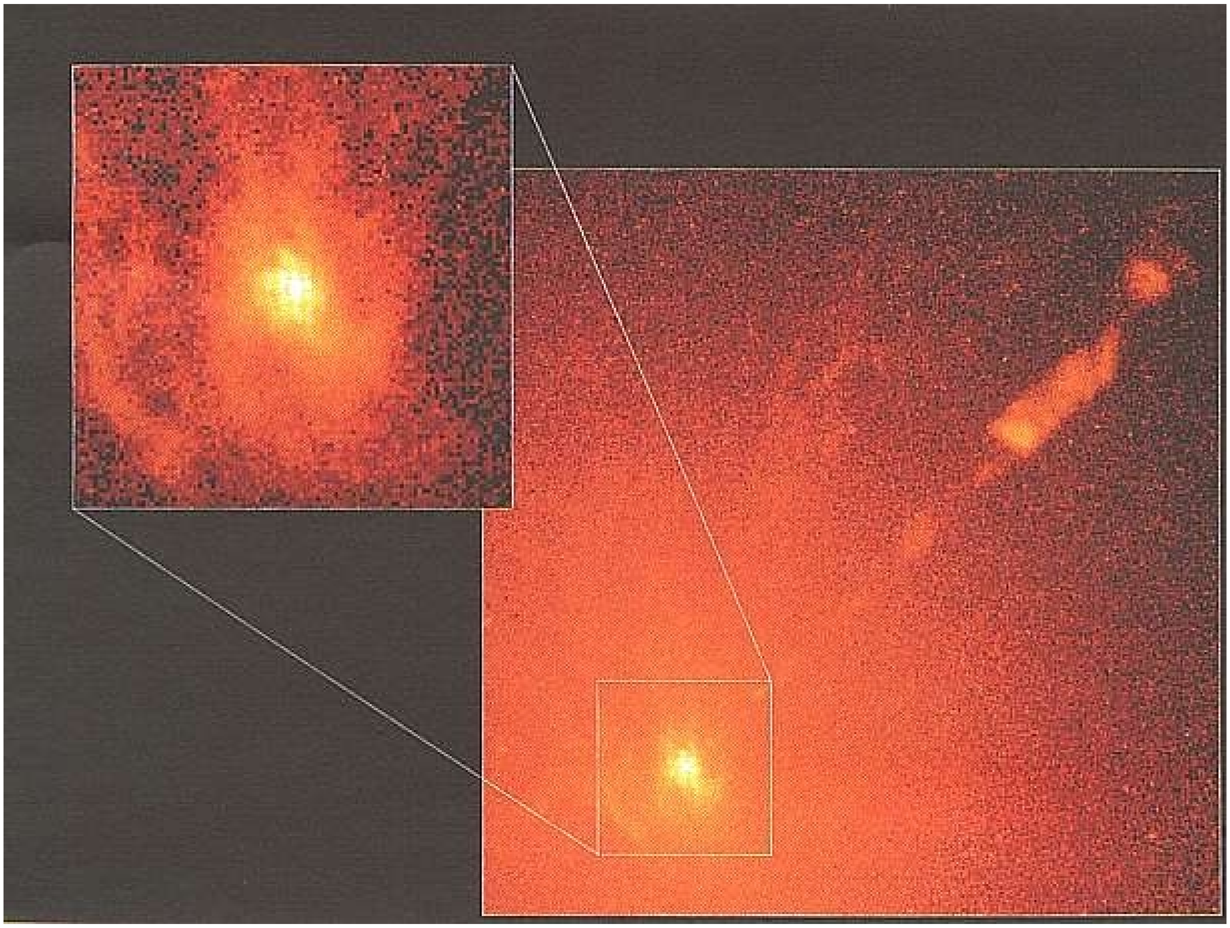

FIGURE 4.3
This HST image of the nearby giant-elliptical galaxy, M87, reveals the existence of a spiral-shaped disk of hot gas in its core (see detail at left). Associated spectroscopic data revealed that the disk is rotating about an extremely massive and extraordinarily compact central object. Indeed, the disk's central regions are so compact that a mass equivalent to that of some 3 billion Suns must be confined within a region no larger than the solar system. The only plausible explanation of these observations is that M87's core contains a supermassive black hole. Another feature indicating the active nature of M87's central regions and signaling its relationship to the more distant and energetic quasars is a jet of high-energy electrons emanating from the galaxy's core and directed toward the upper right. Illustration courtesy of Holland Ford and the Space Telescope Science Institute.

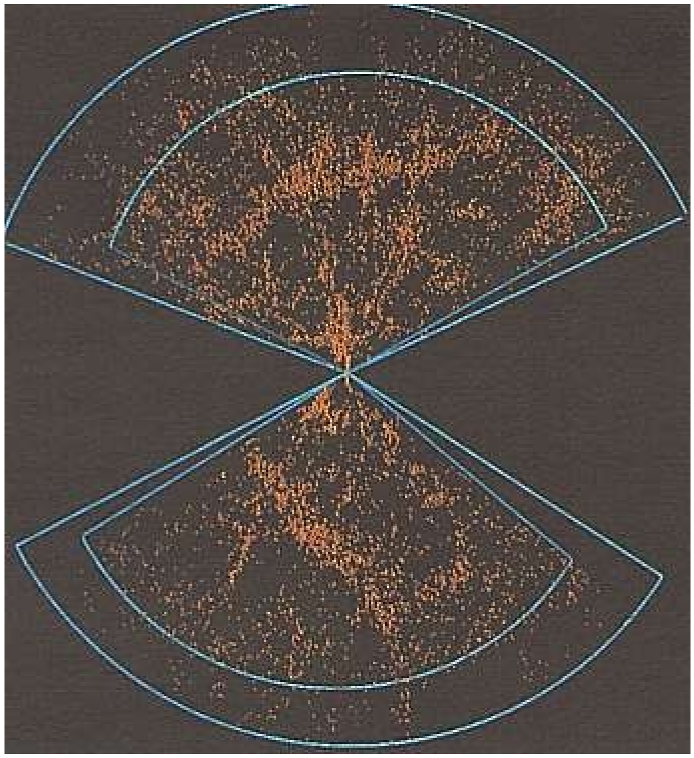

FIGURE 5.1
This map shows the large-scale distribution of galaxies in two wedge-shaped slices of space oriented toward the north and south galactic poles. Each of the 9,325 points plotted represents a galaxy similar to the Milky Way. The arcs forming the northern and southern boundaries of this plot are located at a distance of about 400 million light-years from the Sun. The dark regions to the east and west are obscured by the plane of the Milky Way. The so-called Great Wall, a sheetlike feature containing thousands of galaxies, stretches nearly horizontally across the entire northern (upper) portion of the surveyed region. A similar Southern Wall runs diagonally across the southern region. These walls delineate giant voids containing few if any galaxies. These voids are typically 150 million light-years in diameter. Illustration courtesy of Margaret J. Geller, John P. Huchra, Luis A.N. da Costa, Emilio E. Falco, and the Smithsonian Astrophysical Observatory.

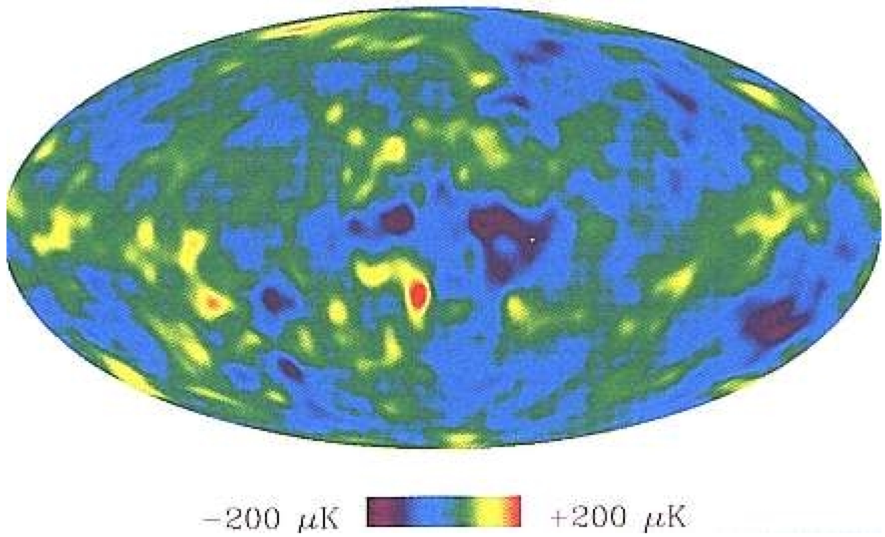

FIGURE 5.2
This false-color image shows tiny variations in the temperature of the cosmic microwave background radiation measured during 4 years of observations by the Differential Microwave Radiometer instrument on NASA's Cosmic Background Explorer (COBE). The blue and red spots correspond to regions of greater or lesser density in the universe some 100,000 years after the big bang. These "fossilized" relics are thus a record of the distribution of matter and energy in the universe at a time before the matter became organized into stars and galaxies. The features traced out in this map stretch across the visible universe today: the largest structures seen by optical telescopes, such as the Great Wall of galaxies (see Figure 5.1), would fit neatly within the smallest feature visible in the COBE map. Image courtesy of the COBE Science Working Group.

3

Stars and Stellar Evolution

Stars and stellar systems are the building blocks of the universe. Stars create most of the chemical elements, and they allow us to explore the laws of physics under conditions impossible to reproduce on Earth. They provide most of the observed light of galaxies and hence are bright signposts that allow the age, scale, shape, and content of the universe to be determined. An understanding of the workings of stars in all their variety is essential to comprehending the universe we see around us.

Astronomers now know that all the objects they observe, from the other planets in the solar system to the most distant quasars, are composed of the same chemical elements found on Earth. All the heavy elements, moreover, were generated by the nuclear furnaces in stellar cores and released into space by the expulsions of matter that end the lives of the more massive stars. Understanding the chemical enrichment of a wide range of environments remains a central goal of astronomy, and one intimately tied to the study of stars.

One of the most exciting recent discoveries in stellar astrophysics was the identification of a new class of binary star systems containing black hole candidates. Rather than orbiting massive stars, as in the case of Cygnus X-l, these black holes generally have low-mass companions. They are revealed by strong, transient x-ray emissions, often accompanied by optical and radio outbursts, and they provide a new wealth of observational detail and a challenge to theories of the origin, evolution, and astrophysical manifestation of black holes. These black hole transients have many properties in common with the more massive variety of black holes thought to reside in galactic nuclei, including their nonthermal spectra and the capability of producing superluminal jets. Therefore, they give the opportunity to deepen our understanding of black holes on all scales.

Exploring stars in all their manifestations allows astronomers to investigate physical conditions that will never be reproduced in terrestrial laboratories. This exploration is critical for the advancement of astronomy and fundamental physics because it pushes models of physical reality to their limits. As the sources of virtually all the visible light of galaxies, stars also provide direct means to make fundamental measurements of distance, age, and mass. An important problem is to resolve the apparent discrepancy in the age of the oldest stars and many measures of the age of the universe. Stellar research can also provide insight into some of the universe's deepest mysteries: the nature of dark matter and the origin of gamma-ray bursts.*

* Dark matter is also discussed in Chapters 4 and 5. Gamma-ray bursts are discussed in Chapter 5.

KEY THEMES

The major scientific goals for the study of stars and stellar evolution can be organized according to the following four themes:

- The life cycles of stars;
- The origin of the elements;
- The behavior of matter under extreme conditions; and
- The use of stars as probes.

The discussion below of each of these themes emphasizes issues for which space-based astronomy is crucial.

LIFE CYCLES OF STARS

Understanding the life cycles of stars, from turbulent clouds of gas to bright beacons of light to catastrophic explosions as supernovae, and hence to rebirth as neutron stars or black holes, remains a central challenge of the natural sciences. The theory of stellar evolution is still largely dependent on the simplifying assumption of spherical symmetry. Accretion disks, bound by stellar gravity but supported almost purely by rotation and forced to evolve by magnetic fields, remain a key topic in stellar astrophysics. To a great extent, the frontiers of stellar astronomy are concerned with the causes and effects of departures from symmetry.

Key Questions About Stellar Evolution

Important questions remaining to be answered about stellar evolution include the following:

- What physical processes determine the mass functions of single and binary stars, from their formation to their demise as compact stellar remnants such as white dwarfs, neutron stars, and black holes?
- How do rotation and magnetic fields influence stellar evolution?
- How are stellar magnetic fields generated?
- What are the progenitors of supernovae and the mechanisms of their explosion?
- Which stars leave neutron star remnants, and which leave black holes?
- How does transfer of mass take place in binary stars, and what regulates accretion onto compact objects?

Recent Progress in Understanding Stellar Evolution

Pre-Main Sequence Stars

During their formation, stars are strongly influenced by rotation and magnetic fields that break spherical symmetry and channel angular momentum. The ubiquitous disks and bipolar flows that regulate stellar rotation through magnetic interaction were resolved for the first time earlier in this decade by means of interferometric observations at millimeter wavelengths. More recently, spectacular Hubble Space Telescope (HST) images of the young stars in the Orion nebula revealed protostellar disks (see Figure 2.1). It is now clear that most young stars are members of binary systems. Thus even as astronomers have begun to discover candidate disks, they have also been forced to consider the impact of a second star embedded within the disk. Theory predicts that stellar- or jovian-mass companions will tidally clear large gaps in disks. Such tidal effects will fundamentally alter the distribution and flow of mass within the disk. The interaction of rotation and magnetic fields in young stars represents a qualitatively new area of study, one that may deeply change current understanding of stellar evolution.

Stellar Dynamos and Chromospheres

The Sun is still the gateway to a deeper understanding of all stars because it is typical in so many ways. Solar seismology has used oscillations to image phenomena such as the rotational profile of the core and the subsurface convective structure of sunspots. The lessons learned there will apply to stellar convection and magnetic structures in other stars. The properties of sunspots and solar flares constrain theories of magnetic structure and reconnection that aid understanding of these processes in the broader contexts of both stars and accretion disks.

Solar seismology techniques have been extended to other stars. The study of nonradial oscillations in white dwarfs has provided the ability to directly measure masses, radial variations in composition, differential rotation, and magnetic structure. Such studies also hold the promise of determining temperature evolution and hence age. More recently, Delta Scuti stars have been shown to display not only nonradial surface modes, but also radial modes in their deep interior. Space-based observations are crucial to extending this work when the noise from atmospheric turbulence dominates the signal from the stellar oscillations.

Stellar chromospheres and coronae provide clues to the asymmetries that rotation and magnetic fields impose on stellar structure. Substantial features that vary with rotation rate and spectral type exist on the surfaces of both single and binary stars. The Extreme Ultraviolet Explorer (EUVE) and Advanced Satellite for Cosmology and Astrophysics (ASCA) have revealed dense coronal structures and the reconnection and flaring of magnetic fields in young stars. The first image of the surface of a star, the supergiant Betelgeuse, was recently obtained with HST. In rapidly rotating cool stars like Betelgeuse it has been shown that, unlike those in the Sun, magnetic spots frequently occur at the poles. As compared to single stars of the same temperature and luminosity, binary systems show greatly enhanced activity in the ultraviolet and may well show evidence of interaction between components.

White Dwarfs

Space missions over the past decade have produced important breakthroughs in the study of white dwarfs, especially those in close binaries. A combination of HST's high spatial resolution and the Roentgensatellit's (ROSAT's) ability to obtain deep x-ray images has enabled the identification of the long-sought population of white dwarf binaries in globular clusters. These stars are intrinsically interesting as test beds for binary evolution, and they can have a profound effect on the dynamical evolution of the clusters themselves. The physical conditions in white dwarf binaries were clarified when high-resolution ultraviolet spectroscopic observations with HST and the International Ultraviolet Explorer (IUE) identified "iron curtains" formed by a huge number of narrow iron absorption lines that have a major effect on flux distribution. These broad absorption features are seen in the early days of nova outbursts and when a dwarf nova's accretion disk is viewed edge on.

A long-standing problem has been the nature of the boundary layer where the disk impacts the surface of an accreting white dwarf. EUVE spectra of white dwarfs accreting at high rates during dwarf novae outbursts confirmed the theoretically predicted 100,000- to 500,000-K boundary layer. EUVE also provided critical constraints on magnetic white dwarf accretion flow by establishing the vertical extent of the accretion spot and the spectrum of the heated white dwarf.

New insight into the ultimate evolution of white dwarf binaries came from ROSAT observations of supersoft x-ray sources, many of which are accreting white dwarfs undergoing steady nuclear burning on their surfaces so that the white dwarfs are increasing in mass.

Supernovae

The origin of Type Ia supernovae is still a mystery, and fundamental issues of the nature of the explosion process continue to be debated. Recent observations have confirmed that Type Ia supernovae are not standard candies, but instead have a spread in maximum brightness that correlates with the rate of decline of the light. The peak brightness may also correlate with the nature of the host galaxy, and hence the stellar population that produced the supernova.

Astronomers still do not know if Type Ia supernovae arise in a binary system containing a white dwarf and a normal star, two white dwarfs, or some other configuration of stars. The accreting white dwarf supersoft x-ray sources may be related to the progenitors of Type Ia supernovae. As yet, however, there is no clear evidence that these supernovae arise in binary systems at all. Despite these uncertainties, understanding of the physics of the thermonuclear explosions underlying Type Ia supernovae has advanced in a major way with the finding that departures from spherical symmetry are very important.

Massive stars, in excess of 8 solar masses, end their lives by gravitational collapse that triggers supernovae, forms neutron stars and black holes, and ejects a significant fraction of the synthesized elements into space. Supernova (SN) 1987A continues to give insight into that dramatic event. HST images and spectra have given deeper understanding of the multiple rings (Figure 3.1) that may represent a link to the general process of planetary nebula formation. The debris of SN 1987A is expected to collide with the inner ring in about the year 2005, yielding a dramatic intensification of both x-ray and ultraviolet lines.

Other work has shown that Type Ib and Ic supernovae and intermediate spectral class objects like SN 1993J have much to teach about the physics of core collapse and the dynamics of the explosion. Both SN 1987A and SN 1993J show evidence for asymmetric ejection of radioactive ^{56}Ni. The enriched knots of Cas A and "bullets" of ejecta from the Vela supernova remnant also indicate departures from a spherically symmetric shell-like structure.

Great progress has been made in understanding the physics of core collapse based on the recognition that three-dimensional convection is probably critical to the process. The current calculations still cannot give sufficient asymmetry to account for pulsar runaway velocities whose rates are often 500 km/s or more.

Neutron Stars

Neutron stars continue to be an exciting research frontier. ROSAT's observation of soft x-ray emission from single pulsars has supported the idea that the cooling of a neutron star is controlled by ordinary matter in its core, rather than by some more exotic form of matter. One of the most dramatic recent developments in the study of binary neutron stars is the Rossi X-Ray Timing Explorer's (RXTE's) discovery of the long-sought millisecond spin periods in low-mass x-ray binaries. This discovery opens the way to detailed study of the spin history of accreting x-ray binaries and their evolution into millisecond pulsars.

The Compton Gamma-Ray Observatory's (CGRO's) Burst and Transient Source Experiment (BATSE) has verified that torque and spin acceleration are correlated, but has also observed long-term spin down and spin up of accreting pulsars with comparable time scales, in contradiction to popular theories. RXTE has also detected the first millisecond, quasi-periodic oscillations in x-ray binaries. These oscillations give direct evidence concerning physical processes in the inner accretion flow.

Ground-based observations of one pulsar have shown one or more planetary-mass objects in orbit around it. It is not known whether these "planets" existed before the explosion, were somehow formed in the explosion, or instead condensed out of the accretion disk from an evaporated companion.

Black Holes

One of the most surprising recent findings is that many of the soft x-ray transients are very likely black holes with low-mass stellar companions. The all-sky monitoring capability of the BATSE instrument on CGRO has been especially useful in enabling the discovery of these transients and in providing the data required to understand them. There are now six such systems with well-defined mass functions in excess of 3 solar masses. The exponential decline of the light curve observed in many of these systems puts stringent constraints on the nature of the viscosity in the accretion disk and points strongly to an origin in a dynamo driven by internal waves. Ginga, EXOSAT, and now RXTE have found quasi-periodic oscillations and their first harmonics at various frequencies in black hole transients. Many of these frequencies are similar to those of neutron star sources, suggesting a common origin in the accretion process.

Observations of some of these black hole candidates reveal tantalizing evidence for red-shifted annihilation radiation. The companions of some of these systems (and some neutron star systems) show lithium enhancements. The lithium could form in the collision of high-energy particles with carbon or oxygen nuclei in the accretion disk.

The black hole x-ray binary systems have a hard x-ray and gamma-ray spectral component that is very reminiscent of quasi-stellar objects (QSOs) and active galactic nuclei (AGN), and two of them have been observed to have superluminal radio jets. These systems may exhibit the fundamental physical processes at work in quasars in a better-constrained and more directly observable setting.

Future Directions for Understanding Stellar Evolution

Future progress in the study of stellar evolution can be achieved in a number of different ways. These are, in approximately the order encountered in stellar evolution, the following:

1. **Studying nonspherical effects in young stars and protostellar disks**. Young binary stars serve as laboratories to help researchers understand the influence of massive companions on protostellar disks. Similarly, mass functions of young stars, both single and binary, are still very uncertain. With expanded astrometric capabilities and consequent determinations of mass, the nature of binary companions can be definitively established. Infrared spectroscopy will also be useful in helping to determine the radial variation in the opacity of protostellar disks.
2. **Understanding the dynamics, heating, and energy balance of stellar chromospheres**. The size and orientation of surface features on main sequence and giant stars enable differentiation between global pulsations, supergranulation cells, or spots. The discovery of spots on evolved luminous stars would be strong evidence for the presence of magnetic fields that are a possible source of heating and momentum deposition in the outer atmospheres, perhaps providing the energy for a stellar wind. A combination of extreme ultraviolet, ultraviolet, and infrared imaging and spectroscopy is the relevant set of techniques to advance such studies.
3. **Determining the temperature, density, and velocity of the emitting areas on white dwarfs**. Advances in the understanding of white dwarf binary systems in the next decade will come from increasing spectral resolution in the extreme ultraviolet and x-ray bands. Increased angular resolution at high energies will enable the identification of optical counterparts for both isolated white dwarfs and those accreting from binary companions. The ultimate goal of observations at longer wavelengths is to directly resolve the accretion areas in disk and in magnetic systems. The most useful observations will involve large-collecting-area, high-resolution x-ray and extreme-ultraviolet spectrographs. Also important is the capability for long-duration observations (high Earth orbit), a rapid response to transient events, better multiwavelength coordination by optical monitors on board satellites or dedicated ground-based telescopes, and an all-sky ultraviolet survey in the 90- to 300-nm band to locate hot objects, and to correlate findings with those obtained in existing radio, optical, and x-ray surveys.
4. **Verifying the thermonuclear models of Type Ia supernovae**. Gamma-ray spectroscopy should reveal whether the optical output from Type Ia events derives entirely from radioactive decay as surmised, and should be able to provide constraints on the physical models. Gamma-ray monitoring of radioactive species, ^{56}Ni and ^{56}Co, would determine when the explosion occurred. The data on kinematics and timing would give a clear test of models. Detection of the 511-keV emission from Type Ia supernovae would give a direct measurement of the manner in which positrons are emitted from these events. X-ray observations of the supersoft sources and related systems will yield greater understanding of their ultimate evolution and of the state of circumstellar matter that can be ionized by the x rays to give an extended HII region. Better knowledge of the nature of the circumstellar medium may give clues to its prior evolution and the possible connection to Type Ia supernovae.
5. **Understanding the mechanism of core-collapse supernovae**. This task requires gamma-ray observations to determine the quantities of radioactive Ni and its decay products, and whether or not they are ejected axially or otherwise asymmetrically. The element ^{44}Ti is also of significant interest since it is produced near the critical region that divides the mass expelled during the explosion from that which falls onto the neutron star. Gamma-ray observations with a line resolution of several hundred kilometers per second of ^{56}Ni, ^{56}Co, ^{44}Ti, and positronium would provide critical information on the dynamics of the ejecta of radioactive species.
6. **Clarifying the evolutionary histories of neutron stars**. Many issues, ranging from the origin of millisecond pulsars to the fate of old neutron stars and the question of whether or not any of them have high magnetic fields, remain to be clarified. The most useful observations will require large-collecting-area, high-resolution

imagers and spectrographs throughout the x- and gamma-ray bands. Significantly increased angular resolution would aid the identification of optical, infrared, or radio counterparts. There is also a need to determine the spin and magnetic field of neutron stars in low-mass x-ray binaries. This can be done by high-temporal-resolution measurements at soft and hard x-ray wavelengths.

7. **Measuring the density and spatial distribution of old, inactive neutron stars and various types of pulsars**. Only a small fraction of neutron stars are active as pulsars or accreting binary systems. Neutron stars are likely to emit an observable fraction of their luminosity as cyclotron emission, thus allowing a measurement of the magnetic field on old pulsars. A large number of pulsars in our galaxy may be strong gamma-ray emitters rather than strong radio emitters; an important task is to determine the number of active isolated pulsars, the population of gamma-ray pulsars, and the fraction of these that are not powerful radio emitters. This requires high-sensitivity, wide-area surveys of the galactic plane for pulsars at MeV to GeV energies.
8. **Understanding the stellar evolution that gives rise to black hole binaries**. The new class of black hole transients raises fundamental questions about how stellar-mass black holes are formed. Several systems appear to have black holes of only 5 solar masses, which is both too large for plausible collapse of neutron stars and yet too small for formation from the massive helium cores of stars too massive to form neutron stars or supernovae. To better understand these issues, the sample of candidate black holes should be significantly extended by conducting an all-sky, hard x-ray, imaging survey. Follow-up optical and infrared spectroscopy will be needed to measure the system mass functions and black hole masses and thereby determine the mass function for stellar-mass black holes.
9. **Exploring the astrophysical nature of black hole transients**. The physics of accretion disks is reflected in their light curves. Obtaining multiwavelength light curves of black hole transients requires optical all-sky monitors coordinated with both all-sky and detailed imaging and spectroscopic observations at hard x-ray and gamma-ray wavelengths. All current soft x-ray, transient black hole candidates are in the Milky Way. This sample should be extended by a search for black hole x-ray transients in nearby galaxies (e.g., Large and Small Magellanic Cloud and M31) and measurement of their time-dependent, multiwavelength spectra. This task requires large-collecting-area, x- and gamma-ray imaging and spectroscopy. To determine whether the "annihilation" line in some black hole transients is due to positrons or to a blend of spallation gamma rays requires high-resolution, time-dependent, hard x-ray and MeV spectroscopy.

ORIGIN OF THE ELEMENTS

Elements heavier than lithium are produced in stars by complex processes, and quantitative understanding of the chemical enrichment of the Milky Way and external galaxies is still rather primitive. Variations in metallicity as a function of position within the Milky Way and as a function of the redshift of more distant galaxies may provide important clues in this area. In addition, further progress is required in the theoretical understanding of mixing processes within stars and of the quiescent and violent ejection mechanisms that release processed stellar material back into the interstellar medium.

Key Questions About the Origin of the Elements

- How do mass loss and mixing influence stellar evolution and nucleosynthesis?
- What are the physical mechanisms that cause loss of mass from stars, and why is loss of mass so often bipolar?
- What elements are ejected in novae and supernovae?
- How does the relationship between age and metallicity vary with location in the Milky Way and elsewhere?
- How did quasars manage to produce a solar distribution of heavy elements so quickly?
- What are the mechanisms by which globular clusters and the lowest-metallicity stars are enriched?

Recent Progress in Understanding the Origin of the Elements

Mixing

Mixing is a major factor in current uncertainties in models of stellar evolution and nucleosynthesis. Convection is the primary mixing process in stellar astrophysics, and it is not well understood beyond the heuristic level of the one-parameter, mixing-length theory. At some level, convection is the issue preventing further understanding of stellar evolution at every stage. This is especially true both when dynamical or rapid evolutionary circumstances demand a proper, time-dependent theory of convection, and in the face of compositional inhomogeneities that affect even the criteria for convective stability in nontrivial ways. These problems are of fundamental importance for the understanding of nucleosynthesis, the evolution of single and binary stars, and the use of stars as chronometers.

The last decade has provided considerable evidence that convective mixing occurs at stages where standard, nonrotating, nonmagnetic theories predict no mixing. In many cases, the mixing cannot be attributed to convection.

It is now clear that the ratio of ^{12}C to ^{13}C already is anomalous in stars barely evolved off the main sequence or up the subgiant branch. This observation implies a mixing to the surface—by a mechanism that remains unknown—of material that has been subject to nuclear processing in deeper layers. Mixing could be induced by some form of meridional circulation and turbulence driven by rotation. Turbulent diffusion might be especially important for massive stars that are radiation-pressure dominated and closer to neutral dynamical stability. In evolved stars, mixing between the interior and the surface is controlled by the depth of penetration of the deep, outer, convective envelope. Observed surface compositions again have revealed abundances created in the deep interior that are not predicted by the standard mixing theory for low-mass stars.

In evolved, red-giant stars, substantial nucleosynthesis occurs specifically in thermal pulses in the helium-burning shell. Observations of red giants show that mixing from the shell occurs over a wider range of mass and metallicity than current theory predicts. An important factor may be overshoot driven by turbulence and, again, involving rotation. In massive stars the mixing, and hence the star's evolution, are thought to be strongly influenced by gradients in the composition and the accelerating pace of evolution that can become comparable to the mixing circulation time.

Mass Loss

Winds and other forms of mass loss from stars remove mass and angular momentum and hence may profoundly affect stellar evolution and nucleosynthesis. The mechanisms of mass loss may in turn be influenced by rotation and magnetic fields. While all main sequence stars lose mass in winds, this process is especially severe in massive stars whose mass can be substantially depleted on the hydrogen-burning time scale. While great progress has been made toward understanding spherically symmetric, radiation-driven winds emanating from massive stars, there are still difficulties in understanding time-dependent, nonspherical mass loss in massive stars such as luminous blue variables and Wolf-Rayet stars. Discovering the mechanisms responsible for mass loss from massive stars in all their variety is key to understanding their later evolution and nucleosynthesis. Ultraviolet spectroscopy has provided deeper understanding of the physics of radiatively driven winds from massive main sequence stars and Wolf-Rayet stars.

The subject of planetary nebulae still contains a variety of astronomical puzzles. The ejection process carries matter, some of it newly synthesized, into the interstellar medium and leaves behind a white dwarf, the most common form of compact remnant. Recent work has made abundantly clear that planetary nebula ejection is not spherically symmetric (Figure 3.2). Bipolar flow is the norm, and more complex flow patterns have been revealed by HST images, most recently those of spectacular "globules" or "fliers" of ejecta. Does bipolar or more complex flow demand a binary companion, or can a single star manifest such complexity? Mass loss continues even after envelope ejection. As with main sequence and Wolf-Rayet stars, ultraviolet spectroscopy is the key technique for investigating the physical mechanisms responsible for radiatively driven winds coming from the nuclei of planetary nebulae.

Supernovae

Supernovae play a major role in nucleosynthesis. They create all the chemical elements more massive than carbon and much of the carbon as well. In the last decade, multiwavelength studies of supernovae and associated theory, especially of SN 1987A, have brought us closer to a quantitative understanding of how the major elements are made in supernovae. The role of neutrinos from gravitational collapse in forming nuclei via the r-process has been clarified, although much about the process remains unknown. There has been progress in understanding how age-metallicity relationships and correlations of key elements depend on stellar kinematics and position in the galaxy, but the full role of the contribution of thermonuclear and core-collapse supernovae to determining the chemical enrichment of stars of all ages and in all environments is still elusive.

As a supernova explosion expands into interstellar space, it heats the ambient material to x-ray temperatures and seeds it with ejecta. Atomic transitions in the x-ray regime provide signatures of the elements present in supernovae remnants. Theoretical plasma models yield abundances and hence a quantitative determination of nucleosynthesis at the sites of specific events. ASCA, the first true imaging spectrometer in the x-ray band, directly imaged supernova remnants in individual atomic transitions of recently expelled elements. These data, together with higher-resolution spectral imaging now being conducted by the Satellite per Astronomia in Raggi X (SAX), are providing, for the first time, the opportunity to determine the composition of the contents ejected from the cores of massive stars.

Future Directions for Understanding the Origin of the Elements

Future progress in the study of the origin of the elements can be achieved in a number of different ways. Among these are the following:

1. **Understanding variations in the relative abundances of the elements throughout various phases of stellar evolution**. Observational investigations pertaining to stellar mixing are hampered by the lack of reliable measurements of distance and hence estimates of luminosity. Accurate measurements of the parallaxes of a large sample of red giants would greatly ease this problem. A marked characteristic of most galactic globular clusters is that all stars within a cluster have essentially the same metallicity. However, detailed studies of the chemical compositions of giant stars in globular clusters have revealed star-to-star anomalies that may indicate nucleosynthesis and mixing within individual stars at levels not predicted by standard theories of stellar evolution. Studies of faint main sequence stars will indicate the extent to which abundance anomalies arise because of mixing or because the cloud from which the cluster formed was inhomogeneous. Many of the key resonance lines of heavy elements, especially those created by the r-process, fall in the ultraviolet and hence require space-based observations. In general, progress in understanding the physical mechanisms of convection and mixing will depend on careful observations of a range of elements that are synthesized under different conditions of density and temperature, e.g., ^{7}Li, ^{12}C, ^{13}C, ^{16}O, ^{17}O, and ^{18}O.
2. **Discovering the fundamental mechanisms of mass loss**. To discover such mechanisms will require high-spatial-resolution ultraviolet, optical, and infrared observations close to the surface of stars losing mass. Observations are also needed of circumstellar shells at a large distance from the star with millimeter and far-infrared interferometers and molecular emission lines. High-resolution optical and infrared imaging is necessary to determine the mass-loss history and the distribution of dust and molecules in planetary nebulae. Ultraviolet and x-ray spectroscopy is necessary to determine nebular abundances and correlated properties of the central star and winds.
3. **Understanding the process of planetary nebula ejection**. This process, linking pulsating red-giant stars to white dwarfs, is poorly understood. Moreover, it has parallels with other mass-ejection processes in objects ranging from protostars to supernova progenitors. Recent HST images have revealed compact knots in the ejecta

of both planetary nebulae and supernova remnants. These Observations suggest underlying similarities in the physics of stellar mass ejection. An intense wind is suspected, but the physics of this process is not well understood, nor is the role of stellar pulsations. Direct determination of distances via measurement of the parallaxes of a large number of planetary nebulae would lead to greater understanding of the formation and evolution of the ejected shells and the evolution of the central stars.

4. **Improving quantitative understanding of the physics of supernovae and associated nucleosynthesis**. Of particular importance to the multiwavelength spectroscopic studies required to address this task are observations in the infrared, where lines of important species are unblended and easier to analyze. Also important are gamma-ray observations of freshly produced radioactive species such as ^{56}Ni, ^{56}Co, ^{44}Ti, and positrons. The pioneering work of ASCA should be followed in the coming decade with studies of spectra of supernova remnants of sufficiently high resolution that temperature, density, ionization state, and abundance effects can be sorted out and abundances can be deduced. Because ^{44}Ti has a relatively long half-life, its 68-, 78-, and 1,100-keV lines might be measured by future missions with imaging, hard x-ray Spectrometers of high sensitivity and high resolution. Such measurements would clarify the physics of the explosion, the abundances ejected, and the nature of the remnant.

BEHAVIOR OF MATTER UNDER EXTREME CONDITIONS

Some of the most challenging problems in astrophysics concern the behavior of systems under extreme conditions. Compact stars are among the most important and interesting in this regard. Because of the large gravity they generate, the natural form of radiation is in the x- or gamma-ray bands. Study of these bands is done uniquely or most efficiently from space.

Key Questions About the Behavior of Matter Under Extreme Conditions

Leading questions to be addressed include the following:

- What is the equation of state of neutron stars, and do so-called strange-matter stars exist?
- What is the mechanism by which pulsars emit their radiation?
- Is Einstein's general theory of relativity correct in the strong-field limit characteristic of the innermost orbits around black holes?
- How do black holes create relativistic jets of matter, and what is the composition of the jets?
- How does matter behave near the event horizons of black holes?

Recent Progress in Understanding the Behavior of Matter Under Extreme Conditions

Equation of State of Neutron Stars

Determining the equation of state of neutron star matter promises deeper understanding of nuclear physics and perhaps of more-exotic particle physics. One of the keys to determining the equation of state of a collapsed star is measurement of its mass. Binary radio pulsars provide accurate indications of neutron star masses that seem to fall within 10% of 1.4 solar masses. The masses of neutron stars accreting in binaries are less accurately known, but some are near 1.4 solar masses. If this is the upper limit to a neutron star's mass, as has been suggested, it has important implications for the equation of state.

Different equations of state yield different masses and radii for neutron stars, so that the measurement of these can distinguish between different equations of state. The radii of neutron stars can be determined from their spectra and luminosities. Thermonuclear flash bursts and temperature variations on old, cooling neutron stars have provided relevant estimates of the radius, but in both cases other processes can distort the results, thus limiting their accuracy.

Pulsars

Recent measurements of the light curves of gamma-ray pulsars by CGRO's Energetic Gamma-Ray Experiment Telescope (EGRET) show encouraging confirmation of the predictions of "outer-gap" models of the pulsar emission mechanism. Fits to these light curves enable determination of a pulsar' s magnetic field and the orientation of its dipole-field axis relative to its spin axis. ROSAT and ASCA observations have provided evidence for thermal x-ray emission from isolated pulsars. Such measurements place constraints on neutron star cooling and on the conductivity of the stellar surface.

Strong Gravity

The binary black hole candidates may give the best opportunity to observe astrophysical processes subject to strong gravity. Fluxes and temperatures obtained from x-ray observations of some binary black hole candidates show an inner accretion-disk radius that seems not to change with mass flow rate and is consistent with the size of the last stable circular orbit about a black hole. Recent observations with RXTE have discovered long-lived oscillations in the x-ray emission from at least one black hole candidate that may be a signature of the Keplerian frequency of the last stable orbit around the black hole. Measurement of this frequency yields an estimate of the black hole's mass as a function of its angular momentum, thereby indicating whether the black hole has Schwarzschild or Kerr geometry.

Jets

Jets are phenomena common to protostellar disks, planetary nebula, accreting stellar black holes, and galactic black holes but are not, interestingly, an obvious product of accreting neutron stars. Some bipolar flows are slow and some are relativistic, but all require some form of collimation. Jets associated with stellar black holes are especially interesting since they may be related to similar phenomena in active galactic nuclei. The outflows from black hole sources may involve large fluxes of positrons.

Future Directions for Understanding the Behavior of Matter Under Extreme Conditions

Progress in the study of matter under extreme conditions can be achieved in several ways. The leading ones in priority order are as follows:

1. **Searching for spectral and temporal characteristics unique to black holes**. How can astronomers discriminate between a solar-mass black hole and a solar-mass neutron star, and how can they determine if a black hole has Kerr or Schwarzschild geometry? Black holes will have no hard surfaces as would strange-matter or quark stars. The absence of surfaces can be demonstrated by detecting emission from very close to the black hole's event horizon, including matter orbiting in the last stable orbit. A large collecting area is required to obtain a good signal-to-noise ratio, and hence accurate x-ray power spectra down to the microsecond level for a larger sample. The time-dependent, x- to gamma-ray spectra of black hole candidates must also be determined with x- and gamma-ray observations of high temporal and spectral resolution, and hard x-ray imaging may help to detect and locate a much larger sample of black hole candidates.
2. **Determining the geometry of the jets and characterizing the environments in the vicinity of the black holes creating them**. Performing this task requires measurement of the emission spectrum of the black hole on time scales ranging from minutes to weeks in radio, infrared, x-ray, and gamma-ray bands. The x- and gamma-ray observations provide information on the most energetic and shortest-time-scale processes powering the jet. X-ray lines can give the charge state in the flow, which can be related to the continuum flux and which gives specific diagnostics of the density and flow instabilities. Gamma-ray spectroscopy with relatively high energy resolution will allow measurement of the stability of pair plasmas, their compactness parameters, and the conditions that give rise to them. Radio and infrared observations are needed to characterize the temporal and spatial history of the ejection of matter.

3. **Constraining the equation of state of neutron stars**. To determine the mass and radius of a neutron star and thereby constrain its equation of state requires simultaneous measurement of the Stark broadening of its lines and the gravitational redshift from its surface. This can be done using high-resolution x-ray spectroscopy of appropriate lines of oxygen and iron, or perhaps using pair annihilation lines with high-resolution gamma-ray spectroscopy.
4. **Determining the sites and mechanisms of particle acceleration in young pulsars**. The high-energy emission from isolated pulsars is a long-standing and poorly understood problem. In particular, does outer-gap or polar-cap emission occur? Understanding this requires high-sensitivity MeV to GeV observations of isolated gamma-ray pulsars to determine the pulse profiles, spectra, spin periods, and spin-down rates. Broad wavelength coverage from radio to gamma rays is critical to exploring diagnostics of relativistic motion.

STARS AS PROBES: MEASURING THE UNIVERSE

Stars are the beacons by which we measure the universe—the basic yardsticks for distance measurement. They are also the absolute chronometers of galaxies and thus of the universe, and they provide a sample of the conditions in the cores of dense clusters and galactic nuclei where massive black holes may result from stellar collisions.

Key Questions About Stars as Probes

Answers to a number of important questions remain to be found. These include the following:

- What are the absolute luminosities of stars, and how do they depend on metallicity and galactic environment?
- What are the ages of globular clusters?
- How do dense star clusters and galactic nuclei form and evolve?
- What fraction of the dark matter is composed of brown dwarfs and compact objects (white dwarfs, neutron stars, and black holes)?

Recent Progress in Understanding Stars as Probes

Distance Scales

Measuring distances has always been one of the most fundamental and challenging tasks of astronomy. Astronomers have developed an array of clever indirect methods, but these tend to be rife with systematic errors and are often built on chains of argument that are only as good as their weakest link. In addition, many of these methods are purely empirical and hence not grounded in fundamental understanding of the physical processes involved. Examples are those based on observations of Cepheids, planetary nebula luminosity functions, surface-brightness fluctuations induced by the brightest giant stars in a galaxy, and supernovae. Work on the HST has extended the Cepheid distance scale to the Virgo cluster, a previously inaccessible distance that allows comparison to several competitive methods.

Stellar Evolution and Age Scales

Extensive efforts have been made in the last decade to check the age of globular clusters based on standard techniques of isochrone fitting with attention to the details of metallicity-dependent opacities. White dwarf sequences have recently been measured in globular clusters with HST and the upper end used to calibrate the cluster distance and hence the age from the main sequence turnoff. Cooling of white dwarfs has given a new technique to determine the age of the Milky Way's disk. This technique tends to give a substantially smaller age than do measurements involving globular clusters. Yet another means to measure the ages of stars has been by radioactive dating through the use of the spectral lines of thorium or other radioisotopes.

Dynamics

Ultraviolet imaging with HST has provided important new information on the contents of globular clusters. Star densities near the cluster cores may be as much as a million times larger than those in the solar neighborhood. The stars inhabiting the central core reflect both the stellar evolution and the dynamical evolution of the cluster. HST's images and spectra have provided direct evidence in the cluster cores of significant populations of both merged and stripped stars. Understanding the evolution of these objects presents new challenges for stellar astrophysics.

Dark Matter

Astronomers cannot be confident that their current ideas on the evolution of galactic structure, the chemical elements, or the global structure of the universe are correct until they have determined the nature of the dominant dark matter. If a significant fraction of dark matter is baryonic, ideas about stellar evolution and nucleosynthesis will require revision. If exotic particles constitute the dark matter, the required new physics may force adjustments in both adopted primordial abundances and subsequent stellar evolution and element synthesis.

Searches for massive compact halo objects (MACHOs) have turned up microlensing events that indicate small stellar objects that may or may not be white dwarfs. The years 1995 through 1997 have brought definitive evidence for the existence of "brown dwarfs," stars too small ever to burn hydrogen, but large enough to shine from their own energy of contraction (and perhaps from deuterium burning) and therefore not planets. These brown dwarfs have been imaged as companions to other stars and identified spectroscopically by atmospheric methane features that indicate a low temperature. As yet nothing is known about the density of isolated brown dwarfs. Aside from their potential role as dark matter in the galaxy, brown dwarfs represent an important clue to low-mass star formation, star-formation efficiency, and binary mass ratios.

Future Directions for Understanding Stars as Probes

Additional progress in the use of stars as probes can be achieved with a number of different approaches. These are, in priority order, as follows:

1. **Improving the accuracy of stellar distance measurements by a factor of order 1,000**. Such a capability would expand the volume of space within which accurate distances are available by a factor of a billion and would have an impact on virtually every aspect of astrophysics. Space-based optical interferometers now under consideration may yield high-dynamic-range imaging with milliarc-second resolution. They should also be capable of measuring absolute parallaxes with microarc-second accuracy and proper motions to a precision of a microarc-second per year. Such an interferometer could provide direct measurements of distances for stars of virtually all spectral types throughout the Milky Way. These data would allow qualitatively new studies of galactic structure, today plagued by uncertainties of 10 to 20% for such basic quantities as, for example, the distance to the galactic center. With the galactic structure and total-luminosity measures so derived, a wide variety of secondary distance calibrators can be utilized that would aid extension of the Cepheid distance scale to distant galaxies.
2. **Improving the accuracy of measurements of stellar masses from interferometric studies of the dynamics of binary systems**. Measurements of stellar masses are critical to all of stellar astrophysics and especially to calibration of relationships between mass and age. For normal binaries as well as those with compact components, substantial progress can be made by accurate interferometric measurement of the orbital motion of the system's center of light. Data on this motion, coupled with observations of Doppler shifts, will give a binary star' s orbital inclination, and thus stellar masses, with unprecedented accuracy.
3. **Understanding the physics and evolution of Type Ia supernovae to enable their use as cosmological probes**. Type Ia supernovae hold great promise for determining the cosmic distance scale and the value of the deceleration parameter, and with this information it may be possible to put constraints on the cosmological constant. Current searches are routinely discovering Type Ia events at a redshift of about 0.5, with the current

record in excess of 0.8. To incorporate Type Ia and core-collapse supernovae as useful cosmological probes, astronomers must understand their origin and explosion mechanisms, and how these correlate with the stellar population in which they reside. A key objective is to compile a large sample of supernovae as a function of galaxy type, location in the galaxy, and age of the galaxy (redshift). Such a survey requires a capability to detect supernovae at large redshifts where key spectral features are displaced out of the optical band. This topic is discussed further in Chapter 4.

4. **Performing absolute checks on models of stellar evolution and age**. A key step to determining accurate stellar ages is the precise measurement of distances and hence luminosities. Accurate distances will serve to indicate the turnoff and to normalize the isochrones of globular clusters, the principal tool for determining cluster ages. In general, precise absolute distances and hence luminosities would give an absolute calibration of the Hertzsprung-Russell diagram in a variety of contexts.
5. **Using globular clusters as laboratories for tests of stellar dynamics and evolution**. The fate of blue stragglers and stripped giants remains to be determined with high-resolution images and spectra and with theoretical studies. The origin and evolution of white dwarfs and neutron stars in globular clusters, and thus both initial mass functions and the dynamical evolution of clusters, can be studied with high-resolution optical, ultraviolet, and x-ray imaging. Precise positions of stars in globular clusters can be derived from interferometric astrometry, and binary stars in globular clusters can be studied by very high resolution imaging from optical to x-ray wavelengths. When combined with new absolute measures of distances for stars, these data will allow the use of stars in globular clusters as probes of both internal motions within the clusters and the clusters' motion in the galactic gravitational field. This capability would give greater insight into equipartition and tidal-disruption time scales for the clusters in the Milky Way's gravitational field, and would allow much deeper study of the effects of cluster binaries and their influence on cluster evolution, the approach to equipartition, and their role in the gravothermal catastrophe.
6. **Discriminating between baryonic and nonbaryonic dark matter in the Milky Way**. Accurate measurements of the proper motions of stars far from the galactic plane and the galactic center can place important constraints on the distribution of dark matter in our galaxy. The discovery that a substantial amount of dark matter has accumulated in the galactic disk would imply that this material is baryonic. Such measurements have the potential to rule out most nonbaryonic candidates and many baryonic ones, and hence would be a critical advance.

CONCLUSIONS

Stellar astrophysics remains at the heart of modem astrophysics. A vigorous program of space-based stellar research will benefit not only stellar astronomy, but nearly every other field of astrophysics as well. From the wealth of research possibilities, TGSAA identified several issues of exceptionally high priority. They are, in priority order, as follows:

1. **Understand the origin and astrophysical manifestations of black holes**. The discovery of a new class of stellar-mass black hole candidates—the soft x-ray transients—promises to revolutionize current understanding of these exotic end points of stellar evolution. The fact that these candidates have known binary systematics, accretion disks, and jets makes them especially fruitful laboratories to understand black hole astrophysics, and, perhaps, to probe the nature of strong gravity. Extending the frontiers of stellar black hole research calls for all-sky monitors and hard x-ray imaging surveys to discover new candidates and also calls for higher spatial and spectral resolution throughout the high-energy band. Also needed is temporal coverage on time scales from submilliseconds to years.
2. **Study the behavior of matter at extremes of gravity, rotation, magnetic field, and energy density**. These conditions are best investigated by studying compact objects, especially those accreting in binary systems, using high-spatial- and high-spectral-resolution observations conducted at multiple wavelengths, with particular emphasis on the high-energy bands.
3. **Investigate fundamental issues concerning the origin of the elements** . High-spatial- and high-spectral-resolution observations in the infrared, ultraviolet, x-ray, and gamma-ray bands and fundamental calibrations of

stellar distances are needed to better understand the origin of the elements from the youngest galaxies and quasars to the most recent supernovae and supernova remnants. Key related topics are the roles of rotation and angular momentum in the stars, mass loss, mixing, and the mechanisms of explosion.

4. **Improve understanding of stars as markers of the size and age of the universe**. The use of stars to measure the cosmological distance scale, deceleration parameter, and age of the universe is central to modem cosmology. Important tasks include accurate determinations of the parallax distances and hence ages of globular clusters. Also important are the detection and physical understanding of a large sample of distant supernovae, where most of the flux will be in the infrared.
5. **Understand the effects of rotation and magnetic fields, and the effects of binary companions**. Young stars already provide special insight into these key unknown areas of stellar evolution. Significant progress in understanding the evolution of young stars and their disks, jets, and possible planets can be made with very high resolution imaging.

4

Galaxies and Stellar Systems

Many decades of observations have revealed that our home galaxy, the Milky Way, is a system of a hundred billion stars and is one of many hundreds of billions of similar systems distributed throughout space. The Milky Way is a huge "ecosystem" of stars and gas that circulates and mixes the heavier elements—enriched by each succeeding generation of stars—from which our world and we ourselves are made. Moreover, just as stars are the building blocks of galaxies, so galaxies are the building blocks of the universe. As such, their distribution on the sky can be used to map the large-scale distribution of matter in the universe.

Galaxies contain interstellar gas and dust, the raw materials out of which new generations of stars are born. As these stars age and eventually die, they eject some of their mass back into space, where it mixes with ambient gas and later forms the next generation of stars. This ejected gas is enriched in elements from carbon to uranium formed as a consequence of nuclear reactions in stars. As a result, each succeeding generation of stars will have a chemical composition different from that of its predecessors. The internal structure of a star depends on its chemical composition, and so do its other properties, including how long it will live. Moreover, the chemical composition of the material in dense clouds—the sites of new star formation—determines the cloud's transparency, and the energy that is trapped influences the conditions under which new stars are born. An intricate variety of complex feed-back mechanisms operate in galaxies.

Still another complication stems from interactions between galaxies and their environment. Neighboring galaxies in groups and clusters interact with each other, raising tides of material by their mutual gravitational attraction. As galaxies move through an ambient hot gaseous medium, as is commonly found in groups and clusters, the interstellar gas in the galaxies collides with the intracluster gas and may be stripped away. Such interactions can drive both the evolution of the galaxies and the evolution of their environment.

There are still many fundamental aspects of galaxies about which astronomers have only a sketchy understanding. A prime example of such a mystery is the nature, amount, and distribution of dark matter in galaxies. Because we know almost nothing about the dominant constituent of the mass, we have only a phenomenological understanding of how the gravitating mass is traced by its luminous part. This in turn limits our understanding of galactic structure and the large-scale distribution of galaxies. Another example of the limitations of astronomers' current knowledge is evident in the exotic phenomena called quasi-stellar objects, or quasars, which for over 30 years have withstood attempts to incorporate them into current understanding of the origins of galaxies and stars.

KEY THEMES

A common thread linking much of the research on distant and nearby galaxies is the delineation of evolutionary paths from the earliest epochs to the present. The various ideas discussed in this chapter can be summarized in the following short list of key themes:

- Development of present-day structures;
- Chemical composition of the universe;
- Dark matter;
- Baryons outside of galaxies; and
- Supermassive black holes and quasar power sources.

DEVELOPMENT OF PRESENT-DAY STRUCTURES

How did present-day structures develop from a universe that was once almost perfectly smooth and uniform? This question has a fundamental significance because the early development of structure was crucial to the concentration of baryons (i.e., familiar matter composed of protons, neutrons, and electrons) that in turn eventually led to the existence of life.

Observations of the cosmic microwave background indicate that the universe in the distant past was hot and extremely uniform. There are only weak fluctuations in intensity which reflect slight non-uniformities in the density of the universe at early epochs; the over- and under-densities amount to only I part in 100,000. These perturbations were the seeds from which stars, galaxies, quasars, and large clusters of galaxies later formed. But exactly how and when the variety of structures seen today formed is still a matter of speculation.

In this picture, galaxies condensed at an early time from gas in the expanding universe. At the present epoch, approximately 15 billion years later, the gas in intergalactic space can be expected to be composed of primordial material that was never incorporated into galaxies, plus any gas that was processed through stars and returned to intergalactic space. A full understanding of the evolution of galaxies thus also requires an understanding of the nature and evolution of the gas between the galaxies.

Key Questions About the Development of Present-Day Structures

Key questions to be addressed in studies of the development of present-day structures include the following:

- How do the distribution of galaxy properties such as size and mass, and the variety of their morphological forms, relate to the physical conditions of the universe in its first billion years?
- What triggered the birth of the first generation of stars?
- What regulated or influenced the rates of formation of subsequent generations of stars that drove the chemical evolution of the Milky Way?

To answer questions like these, researchers need to turn the clock back, stepping through the evolution of galaxies over cosmic time, to the epoch of birth. It is difficult to reconstruct the evolutionary history of a galaxy from the "fossil record," but astronomers have the unique opportunity of viewing the history of the universe directly as it happened, by exploiting the cosmological "look-back" time. Events at great distances are observed after a period of time equal to the light-travel time: the farther away the source of light, the farther back in time it is seen. Astronomers now have the capability to make routine measurements of ordinary galaxies at distances of at least 7 billion light-years (that is, a look-back time of at least 7 billion years), to be compared to the age of the universe of around 15 billion years. These time intervals are large enough that evolutionary changes are expected to be apparent (Figure 4.1).

The distance to a galaxy is measured by the redshift seen in its spectral lines—the higher the redshift, the greater the distance, and the earlier in cosmological history astronomers see the galaxy. As just mentioned, normal galaxies half the age of the universe are now studied fairly easily, but special cases are known of galaxies much more distant and much younger than this—some galaxies are seen when the universe was only 15% of its present age. By extending search techniques to fainter sensitivity levels, observers can expect to see normal galaxies at comparable distances, and special cases to distances that are limited not by instrumentation, but by the sources themselves.

Recent Progress in Understanding the Development of Structures

Images of distant galaxies from the Hubble Space Telescope (HST) have provided direct evidence for the evolution in galaxy populations and morphology with look-back time. This information, combined with ground-based spectroscopic observations with the 10-meter Keck telescope, have led to the first identifications of star-forming galaxies 2 billion to 3 billion years after the big bang. Many of the objects studied appear surprisingly advanced in their formation even at this early epoch.

These early systems contain enormous amounts of gas—enough, perhaps, to be the forerunners of all the galaxies now seen in the universe. This notion has motivated ongoing attempts to detect starlight from galaxies associated with a class of absorption lines seen in the spectra of quasars, the so-called damped Lyman-alpha systems. Similarly, visible galaxies have been associated with metal absorption lines in the spectra of quasars; these correspondences provide powerful probes of the clouds containing these atoms.

X-ray absorption has been detected in sources close to, and perhaps surrounding, bright, high-redshift quasars. In addition, observations of CO at millimeter wavelengths reveal that large masses of molecular gas have been found around some of the highest-redshift quasars, implying enormously energetic star-formation episodes at this early time.

Recent numerical simulations of the evolution of dissipationless particles (including dark matter) and gas are producing a more accurate picture of the universe in its gas-rich, pregalactic phase. It is becoming possible to simulate the early universe with sufficient fidelity to model the formation of a galaxy and to simulate the clumping of hot and cold gas that gives rise to quasar absorption lines. Refined simulations now allow exploration of the mechanisms triggering bursts of star formation and activity in the nuclei of galaxies.

Future Directions for Understanding the Development of Structures

Further progress in the area of galaxy formation and evolution suggests the following three different approaches, in no particular order:

1. **Conducting a census of galaxies to the earliest possible epoch to observe their formation directly**. To see the gaseous precursors of galaxies and the later evolution of interstellar gas clouds and dust will require instruments capable of reaching far-infrared, submillimeter, and millimeter wavelengths. The proposed ground-based Millimeter Array is a good example of the kind of tool needed to make these observations. Further gains can be achieved with a large, cooled space telescope optimized for photometry and spectroscopy in the approximate wavelength range from 20 to 800 μm.

   Facilities like the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), recently installed on HST, and the Space Infrared Telescope Facility (SIRTF) will identify the most luminous galaxies at very early times and will study what happens when star formation occurs at explosive rates in dust-laden galaxies. SIRTF will detect ordinary galaxies to redshifts (z) of ~3,* and more luminous galaxies at higher redshifts.

   The direct observation of starlight in typical galaxies at very early times will require a large-aperture space telescope optimized for the 1- to 5-μm band in the near infrared. With an aperture large enough to achieve 0.1-arc sec images or better, and cooled sufficiently to be limited by the natural background, such a telescope would have the sensitivity to detect galaxies to redshifts of at least $z = 5$, and might be able to search for galaxies at $z = 10$.

* See *redshift* in the glossary for the definition of z.

2. **Studying the structural and kinematic properties of very young galaxies and following the evolution of these properties to the present epoch**. Achieving this goal requires high angular resolution at optical and near-infrared wavelengths, and moderate-resolution spectroscopy over a wide range of wavelengths (to accommodate the range of redshifts). Large ground-based telescopes will contribute mainly to observations at visible wavelengths, over wide fields of view, and where angular resolution better than 0.5 arc sec is not required. Measuring spectral features in the ultraviolet requires space-based instrumentation. Sensitivity in the near infrared is greatly enhanced with space-based instrumentation, partly because of the lower background, and partly because of the higher attainable angular resolution.
3. **Understanding the interactions among stars, interstellar gas, and dust that drive the formation of stars in a galaxy and chemical evolution**. Individual supernovae trace the first generation of stars and can be detected with a low-background, high-resolution, near-infrared telescope. Since these same supernovae enrich the surrounding gas with heavy elements, their detection allows a direct measure of the chemical evolution of the universe.

Some of the light emitted by stars is absorbed by gas or dust and subsequently re-radiated at longer wavelengths before it can escape the galaxy. Information on the dust grains is provided by the continuum re-radiation occurring at far-infrared wavelengths. Information on the gas comes from line re-radiation, in particular, lines in the submillimeter spectral band.

CHEMICAL COMPOSITION OF THE UNIVERSE

The chemical composition of the universe and its variation over time are of great importance. Three minutes after the big bang, the universe consisted of hydrogen, helium, and trace amounts of other light elements. Synthesis of the heavier elements came several hundred million years later, following the formation of the first generation of stars.

Key Questions About Chemical Composition

Thanks to the increasing amount of high-quality spectroscopic data on elemental abundances in stars and in the gas of high-redshift systems, unprecedented progress in the study of the chemical evolution of the universe is possible in the near future. Answers to a number of key questions will guide future understanding of the history of star formation and nucleosynthesis in galaxies. These questions include the following:

- What are the precise values of the primordial abundances that emerged from the big bang?
- How and when were the heavier elements first synthesized and dispersed after the big bang?
- What was the nature of the very first generations of massive stars and associated supernovae explosions?

Recent Progress in Understanding the Chemical Composition

In addition to the hydrogen lines in the Lyman-alpha forest seen in the spectra of distant quasars, other absorption lines have been observed from atoms like carbon, magnesium, and silicon. The presence of these heavy elements indicates that some material has indeed been processed through stars at very early times; indeed, the spectra of most clouds at the earliest epochs show heavy-element lines. The abundance ratio of silicon to carbon can be used, in principle, to measure the star-formation time scale, which is a measure of the time scale for nucleosynthesis in stars. The study of the connection between the hydrogen clouds and those clouds in which lines from heavier elements have also been detected is an active field of research, particularly now that HST has greatly expanded access to ultraviolet wavelengths. Also important is the ability of ground-based telescopes to obtain high-resolution spectra at high signal-to-noise ratios.

X-ray telescopes have discovered that hot diffuse gas is a major component of the mass of rich clusters of galaxies. Moreover, both continuum radiation and line emission are detected at x-ray wavelengths, and the gas is deduced to have a heavy-element fraction as large as that seen in the solar system. These developments have raised a host of new questions. How, in detail, is metal-enriched gas ejected from galaxies, and how does the efficiency of related processes depend on the dynamical state or age of the cluster? How is the intracluster gas heated to such high temperatures? What are the specific contributions to the mix of metals from Type Ia and Type II supernovae, and how have the relative contributions tracked the evolution of the clusters? Visible-light spectroscopic measurements of chemical abundances in the stars in the galaxies, and abundances deduced from quasar absorption lines, have yielded complementary constraints on such issues.

Spectroscopic studies of the stars in the Milky Way's halo have made important contributions to this discussion. These stars are notable because they have extremely low heavy-element concentrations, presumably because they formed very early in the history of the Milky Way. Observations with both HST and ground-based telescopes, have, however, detected signatures of supernova enrichment and thus, perhaps, an epoch of heavy-element synthesis very early in the Milky Way's history.

Studies of stars in nearby, dwarf galaxies give important information about the history of galactic star formation; rather than being simple, as previously thought, the dwarfs display complex episodes of star formation occurring irregularly over much of their lifetimes. Campaigns to detect distant supernovae ($z > 0.5$) have been successful thanks to large-format charge-coupled devices (CCDs), sophisticated image-processing software, and the availability of time on large telescopes; analyses of light curves have yielded key parameters such as the supernova type and the maximum flux. Variations of elemental abundance with time for stars in the Milky Way's disk have been determined, indicating that the mass fraction of heavy elements has increased by only a factor of 3 to 5 over the last 10 billion to 12 billion years. Measurements of the abundance ratio of deuterium to hydrogen in intergalactic gas clouds have provided important constraints on the history of star-formation activity as a function of redshift. These observations have, as a consequence, further tested the predictions of the synthesis of the light elements in the big bang.

Future Directions for Understanding Chemical Composition

The future directions identified below are intended to elucidate the history of star formation, the major factor in compositional evolution. Critical issues to be examined with the next generation of instrumentation include the following, in no particular order:

1. **Measuring the composition of the gas, dust, and stars of which the universe is composed, as a function of redshift**. This requires identification of galaxies (and protogalaxies) to large redshift, and spectroscopy of these galaxies across a wide range of wavelengths. Surveys with SIRTF will provide target lists.
2. **Conducting a census of supernovae at high redshifts to measure their early rate of occurrence**. The rate of occurrence of Type II supernovae is an index of the formation of massive stars. Thus, the rate for Type II relative to that for Type Ia provides a diagnostic of the first stellar generations. This diagnostic, in turn, allows the elemental abundances at high redshift to be interpreted. The detection of supernovae at the greatest distances requires high angular resolution, sky coverage adequate to find these rare events, and a low background in the near-infrared spectral range.
3. **Determining the amount of the hot gas in clusters of galaxies as a function of redshift**. Such a program requires sensitive x-ray spectroscopy. The Advanced X-Ray Astrophysics Facility (AXAF) will begin this program, but higher-sensitivity spectroscopy is needed. Moreover, wide-field capability in the x-ray band is required to identify unbiased samples of distant clusters.
4. **Using intergalactic gas clouds at high redshift to probe the early history of elemental abundances**. High sensitivity combined with high spectral resolution at ultraviolet wavelengths is necessary both to measure important atoms (e.g., neutral and ionized helium) and to compare absorption lines at low redshift with those at high redshift.

DARK MATTER

There is convincing evidence that matter in the familiar form of stars, gas, and dust constitutes only a small fraction of the matter in the universe. The missing mass is 10 to 100 times larger than that which is observed. Some of this missing, or dark, matter must be in the halos of galaxies; more is probably smoothly distributed outside galaxies. Strong theoretical arguments suggest that the density of the universe is close to the critical value required to eventually halt the expansion resulting from the big bang. If so, there must be even more dark matter than astronomers have already inferred from available measurements.

Key Questions About Dark Matter

Our understanding of galaxies, clusters of galaxies, and the universe itself is seriously incomplete until the nature of dark matter is determined. Three key questions are as follows:

- What is dark matter?
- Where is it located?
- How does it influence the evolution of structures in the universe?

Recent Progress in Understanding Dark Matter

Analysis of the gravitational potential of groups of galaxies, clusters, and individual galaxies based on x-ray observations by the Roentgensatellit (ROSAT) and the Advanced Satellite for Cosmology and Astrophysics (ASCA), has shown that much dark matter exists in these systems. Similarly, gravitational lensing of background sources has been observed in images taken with HST and ground-based optical and radio telescopes (Figure 4.2). Lensing by galaxies and clusters of galaxies cannot be understood unless there is dark matter. The discovery of strong lensing by rich clusters shows that the distribution of dark matter probably has a large central cusp. The detection of gravitational microlensing by objects in the Milky Way's halo demonstrates an important new technique that will allow astronomers to probe dark matter in the form of small collapsed objects, such as burnt-out stars.

Comparison of the mass distribution inferred from large-scale galaxy motions with the mass distribution observed as luminous galaxies has been made possible thanks to complete surveys of nearby galaxies. Such studies have given evidence for very large mass concentrations on supercluster scales, and they point to a universe with a density that may approach or equal the critical density.

Future Directions for Understanding Dark Matter

Future directions for the study of dark matter include the following, in no particular priority:

1. **Detecting dark matter through its gravitational influences on the light from distant objects**. For gravitational lens studies, angular resolution and surface-brightness sensitivity are critical. Large-aperture, high-resolution telescopes working at visible and near-infrared wavelengths will greatly increase the number of objects in which gravitational lens effects can be observed.
2. **Searching for fine splittings in the images of point-source-like quasars**. Ground-based telescopes with adaptive optics can achieve very high angular resolution and are well matched to this task. However, adaptive-optics technology is still under development, and the first applications will focus on the near-infrared spectral range. At shorter wavelengths the field of view is very small, which limits the use of ground-based adaptive-optics observations for untargeted surveys for lensed objects.
3. **Studying lensed radio sources**. Much work is still to be done with the Very Large Array (VLA) and now with the recently completed Very Long Baseline Array (VLBA). However, space-based application of very long baseline interferometry (VLBI) will provide the highest angular resolution at radio wavelengths. The VLBI Space

Observatory Program (VSOP) will be limited in its surface-brightness sensitivity, but if successful it will point the way to more sensitive missions.

4. **Measuring mass distributions on supercluster scales (1 degree of arc) by the technique of weak lensing**. Such studies require the development of ground-based, wide-field-of-view cameras with excellent image sharpness and careful control of the uniformity of the image sharpness across large areas of sky. While HST's current cameras have the requisite angular resolution and uniformity, they are limited by their small fields of view. Future surveys of weakly lensed objects will extend current capabilities by obtaining more solid-angle coverage, fainter surface-brightness limits than those achieved in the Hubble Deep Field, and a wavelength range extending into the near infrared.
5. **Tracing the gravitational potential of galaxies and clusters by mapping their x-ray emissions**. Such observations require more sensitive telescopes with large fields of view. While AXAF will represent a giant step forward in resolution and sensitivity, limitations in the size of its mirrors will prevent the application of these techniques to the most distant objects. To extend the work begun by AXAF, large-scale x-ray optics must be developed.
6. **Improving understanding of the large-scale motions of galaxies**. More accurate maps of the distribution of galaxies and more accurate measurements of distance are essential to this task. The Sloan Digital Sky Survey and the 2-Micron Sky Survey (2MASS) will provide some of the information on the distribution. Studies of Type Ia supernovae and surface-brightness fluctuations are particularly promising techniques to provide information on distances. High angular resolution is critical, and HST's potential has not yet been fully realized for such studies. A space telescope with a larger aperture than HST would allow these techniques to be applied at greater distances. Ground-based telescopes equipped with adaptive optics will probably be of great value as well.

BARYONS OUTSIDE OF GALAXIES

If current ideas about the production of elements in the early universe are correct, then a large fraction of all baryonic matter is not contained in observed galaxies. In the standard cosmological picture, approximately 5% of the mass (if the universe has the critical density) is expected to be in the form of baryons, but less than 1% can be accounted for within the visible boundaries of galaxies.

Key Questions About Baryons Outside of Galaxies

Key questions to guide astronomers' studies of the baryons not tied up in galaxies include the following:

- Are these "missing" baryons in large halos around galaxies, or are they distributed uniformly throughout intergalactic space?
- How much primordial gas was left over in intergalactic space after the initial epoch of galaxy formation?
- How can observers identify the gaseous predecessors of galaxies?

Recent Progress in Understanding Baryons Outside of Galaxies

For years, astronomers have had two sets of observations demonstrating that gas exists between the galaxies: as just mentioned, numerous absorption lines seen in the spectra of high-redshift quasars, and x-ray observations of the hot intracluster gas in nearby clusters of galaxies. New insights into the important role played by intergalactic gas in the evolution of galaxies and structure in the universe have come from a variety of sources. These include space missions (e.g., HST, the Hopkins Ultraviolet Telescope (HUT), ROSAT, and ASCA), large ground-based optical telescopes (e.g., Keck), and extensive numerical calculations.

The spectra of distant quasars show numerous weak absorption features attributable to the Lyman-alpha transition of neutral hydrogen in intergalactic gas clouds that lie along the line of sight. Absorption lines associated with this Lyman-alpha forest are exceedingly numerous: several hundred lines per quasar, far too numerous to be attributable to normal galaxies. Also, unlike galaxies, the clouds are more uniformly distributed along the line of sight; they are not clustered as strongly as galaxies. These clouds seem to dissipate as the universe evolves; the forest is densest in the spectra of the most distant quasars and systematically thins out with time. These properties led to the speculation that the Lyman-alpha forest clouds might be pregalactic gas fragments, which later collapsed to form galaxies. However, observations of lines of ionized carbon, oxygen, and silicon now indicate that at the epoch of the forest clouds, stellar processing had already occurred. In addition, ground- and space-based observations of normal quasars and ones gravitationally lensed show that the moderate- to high-redshift structures producing absorption are very much larger than galaxies. Some idea of what these structures are has come from theoretical studies. Numerical simulations of the evolution of the intergalactic medium indicate that the features causing the absorption are typically sheets and filaments, aligned with the sites of future galaxies and clusters. These calculations also suggest that such features are far from dynamical equilibrium. In an important breakthrough, ionized intergalactic helium was detected by both HST and HUT at very high redshift, providing a direct probe of the state of diffuse gas at early epochs.

The Cosmic Background Explorer's (COBE's) observations of the uniformity of the cosmic microwave background rule out a hot intergalactic medium as the origin of the diffuse x-ray background at energies greater than 1 keV. However, theoretical studies indicate that a substantial fraction of the volume of the local universe is filled with a low-density hot gas, which may account for the x-ray background at lower energies.

The major baryonic component seen in local clusters of galaxies is x-ray-emitting gas. If, as most theoretical studies indicate, rich clusters are fair samples of the universe, this result suggests that the density of the universe is only one-third of the critical density. Many poor groups of galaxies have large dark-matter halos as well, and so it may well turn out that a significant fraction of the baryonic dark matter in the universe resides there.

Future Directions for Understanding Baryons Outside of Galaxies

Future directions in the study of the baryons found outside of galaxies include the following, in no particular order:

1. **Measuring physically important quantities such as density, temperature, and velocity shear in inter-galactic clouds**. Future use of quasars as probes of the intergalactic gas requires greater sensitivity at high spectral resolution. This is especially true in the ultraviolet spectral region, which has the richest set of spectral diagnostics. High spectral resolution is required to fully resolve the lines and measure important physical quantities. The Space Telescope Imaging Spectrograph (STIS), installed in HST in February 1997, and the Far-Ultraviolet Spectrographic Explorer (FUSE) will provide useful data but will be able to study only the brightest and nearest sources.
2. **Determining the sizes and geometry of intergalactic structures**. Correlating the hydrogen absorption lines seen in quasars along neighboring lines of sight is the most appropriate technique. However, doing that requires observing faint quasars to increase the likelihood of finding close pairs. A modest gain in the sensitivity of space-based ultraviolet spectrometers should yield a spectacular gain in the number of lines of sight observable. Increased sensitivity will also allow good searches for trace metals and primordial deuterium in the gas. Progress is most likely to come from a combination of groundand space-based efforts.
3. **Studying the physical properties, evolution, and interactions between intergalactic gas and galaxies**. Such studies are best performed by observations of the far-ultraviolet absorption of neutral and ionized helium in intergalactic gas. Currently, HST and HUT can observe helium transitions in the far ultraviolet along just three lines of sight that are unusually clear of near-ultraviolet absorption by hydrogen. In the places where helium has been seen, only very low resolution spectra are currently attainable. Thus, whether the gas is uniformly distributed or clumped in clouds or sheets is unknown. Observing helium along many lines of sight will require a larger telescope than HST, with better ultraviolet spectroscopic sensitivity. Such an instrument, however, need not be as costly as HST since it can sacrifice image quality to gain increased light-gathering power. Until they are replaced, HST's unique near-ultraviolet imaging and spectroscopic capabilities should be maintained and, if possible, upgraded.

4. **Determining the masses of clusters and the chemical composition of the intracluster gas**. While these quantities are calculable from spatially resolved, x-ray spectroscopy, no x-ray instrument currently available combines the requisite high spectral and spatial resolution. Thus, this technique has been limited by the need to make simplifying assumptions such as spherical symmetry and hydrostatic equilibrium, and the neglect of turbulence or clumping. Observations to date are biased toward low-redshift systems because of the low angular resolution of satellites such as ASCA. Future missions such as the X-Ray Multi-Mirror (XMM) mission and AXAF will have improved sensitivity but will allow clusters to be studied only to moderate distances. A large x-ray telescope, with good angular resolution, could push studies of the chemical and dynamical history of the hot intracluster gas to cosmologically significant distances. Such an instrument will also permit studies of the absorption spectra of C, N, O, Ne, Si, and S ions, redshifted to the soft x-ray band, and will provide unique information about the ionization and abundance of the intergalactic gas as a function of time.

SUPERMASSIVE BLACK HOLES AND QUASAR POWER SOURCES

Quasars are characterized by their enormous power output, exceeding that of entire galaxies; their (astronomically speaking) tiny sizes, comparable to that of the solar system; their spectra, which show no characteristic temperature; and, sometimes, their ejection of matter at nearly the speed of light. The high luminosities of quasars allows them to be seen to larger distances, and therefore to earlier times, than any other object in the universe. Surveys show that quasar activity peaked about 2 billion years after the big bang. What is the nature of the power sources responsible for such huge luminosities, and what is the nature of the strong evolution that is observed?

Motivated by these puzzles, researchers have studied quasars over the last 20 years across the electromagnetic spectrum with space-based telescopes. These observations suggest that the energy source is ultimately derived from the gravitational energy of falling matter, in particular, gas that is falling into a black hole that has 1 million to 1 billion times the mass of the Sun. Inevitably the gas acquires a swirling motion as it falls, creating an accretion disk in orbit about the black hole. This gaseous disk suffers frictional (and possibly magnetic) heating to very high temperatures, perhaps creating a corona above the disk. As the resulting light is radiated away (the light observers see as the quasar), the material sinks closer to the black hole, eventually to fall inside the black hole's event horizon, thus increasing the mass of the black hole. In the meantime, new material has fallen onto the accretion disk to replenish the fuel supply.

This picture has a number of testable features. It is predicted, for example, that the inner edge of the accretion disk is hotter than the outer edge, and, to first order, the emergent spectrum should reflect this difference in temperature. The inner edge will be orbiting more rapidly; in fact, the force of gravity this close to the event horizon is so large that effects of general relativity must be included in the calculations. The speed of rotation can be estimated from the Doppler-broadening of x-ray spectral lines. The disk-like geometry has bipolar symmetry, which is in accordance with the double-lobed structure frequently seen. Jets of material that are observed to be moving close to the speed of light are thought to be collimated by the disk and its magnetic field. A good candidate for a source of infalling gas is a surrounding host galaxy, and indeed quasars do seem to lie at the centers of galaxies (which is why they are commonly called active galactic nuclei, or AGN).

While this model has provided a fruitful basis for the interpretation of new data, there are still a number of outstanding questions. Where did the original seed black holes come from? How does material in a galaxy--typically tens of thousands of light-years across--get funneled into a volume that is light-hours across? How is it that the large masses of quasars and their chemical composition both indicate that they are highly evolved objects, yet the most distant quasars are seen so soon after the big bang? Questions like these need to be resolved before astronomers can construct a comprehensive picture of these important objects.

Key Questions About Supermassive Black Holes and Quasar Power Sources

The details of the physical processes governing the formation and growth of supermassive black holes, the prodigious luminosities of quasars, and the evolution of quasars (both collectively and individually) are still far from being resolved. Key questions in this area include the following:

- What is the specific connection between the observed early peak in quasar activity and the formation history of massive black holes?
- How big are the "seeds" of massive black holes and how fast do they grow?
- Do all galaxies harbor a large black hole?
- Do galaxy mergers lead to black hole mergers?
- Do quasars store up all their fuel early on, or do they acquire it gradually from outside? (If the fuel supply is stored, what turns the supply on and off? If the fuel supply is acquired from outside, what brings the fuel in?)
- How does matter interact with supermassive black holes close to the event horizon?
- How are energetic jets formed and collimated by the black hole?
- Why do some active galactic nuclei apparently never form jets?

Recent Progress in Understanding Supermassive Black Holes and Quasar Power Sources

If quasars are considered as marking the locations of supermassive black holes, an empirical statistical picture of the origin and growth of supermassive black holes can be made by conducting a census of quasars up to high redshifts and down to low luminosities. On the other hand, to study the power sources of quasars requires a complementary approach, namely observing the detailed processes at work in the central regions of individual objects.

Quasars are now known to a redshift of almost 5, corresponding to a time when the universe was less than 10% of its present age. However, at this early time they appear in reduced numbers, suggesting that observers are close to seeing the epoch of initial quasar formation. A potentially large population of quasars not evident from visible-light surveys was uncovered among x-ray and far-infrared sources. This finding suggests that many quasars may be obscured at visible wavelengths by surrounding dust. Careful studies of the host galaxies of quasars by HST and ground-based infrared imaging have revealed much new information. Moreover, similar observations have revealed low-power activity in the nuclei of many nearby galaxies (Figure 4.3).

A number of significant advances in the study of quasar power sources have been made in recent years. Some important examples include the following:

- The VLBA and HST were used to measure the masses of black holes in quasars. Having reliable masses sharpens the problem enormously and makes more detailed tests possible.
- ASCA discovered extremely broad x-ray lines, showing the imprints of strong-field general relativity. This is a first in astrophysics and a clear signature of black holes. The lines come from matter close to the event horizon and tell us the spin of the black hole; potentially they could reveal much more.
- The Energetic Gamma-Ray Experiment Telescope (EGRET) on CGRO revealed that blazars, the most active of galactic nuclei, emit most of their power as previously unobserved high-energy gamma rays. This observation confirmed the hypothesis that blazars contain energetic jets of matter moving toward us at close to the speed of light.
- Features such as shocks moving along quasar jets at 5 to 10% the speed of light and surprisingly small and complex inner structures of active nuclei were mapped by applying the powerful technique of reverberation mapping. The technique relies on a combination of observations from multiple satellites covering visible to gamma-ray wavelengths and takes advantage of the intrinsic variability of the AGN to map structure surrounding the nucleus at scales too small to be resolved directly. The time delay between an increase in the continuum strength and a corresponding increase in line-emission strength, given plausible assumptions, reveals the location of the line-emitting gas relative to the photoionizing source. Similarly, in a blazar undergoing a flare, the delay in the appearance of the flare at different wavelengths reflects the time of propagation of a shock down the jet itself.
- Short-lived analogs of quasar jets have been associated with binary star systems near the galactic center, according to observations made by the CGRO and ground-based radio and millimeter-wave telescopes.

Future Directions for Understanding Supermassive Black Holes and Quasar Power Sources

Progress on the origin and growth of supermassive black holes requires a more complete census of quasars than is currently available. Progress on quasar power sources requires measurements that reveal processes at still smaller physical scales. To answer the key questions relating to supermassive black holes requires the following necessary efforts:

1. **Searching for quasars out to the highest redshifts, including dust-obscured quasars, in the x-ray and far-infrared bands**. AXAF and SIRTF will make deep surveys for obscured quasars; both will also search for the most luminous obscured quasars at the highest redshifts. Surveys for dust-enshrouded early quasars can also be undertaken with large, near-infrared and far-infrared telescopes. An x-ray telescope with 100 times the sensitivity of AXAF and XMM is needed to search for less luminous, obscured quasars, some of which may be in the process of formation. Good angular resolution is needed for reliable source identification at these faint levels. A wide field of view (10 to 30 arc min) is needed to obtain adequate numbers of quasars for statistical studies.
2. **Examining the nuclei of nearby galaxies for weak activity and dormant black holes**. Ultraviolet imaging and spectra and x-ray imaging can be used to look for faint active nuclei in nearby galaxies. Good angular resolution (subarc second in the ultraviolet and optical bands, arc second in the x-ray) is needed to resolve the galaxy in whose nucleus the quasar resides. The current instruments on the HST are well suited to detect weak active nuclei in nearby galaxies. A large collecting area in the x-ray band (100 times that of AXAF) is essential to gather enough photons from nearby, low-luminosity nuclei to study their spectra and variability. Radio sources with no recent injection of relativistic electrons radiate most strongly at low frequencies because the high-energy electrons responsible for high-frequency radio emission lose energy relatively quickly via synchrotron radiation. A low-frequency antenna could search for such relic radio sources. A location far from Earth, e.g., the far side of the Moon, would shield such a telescope from the serious limitations of telecommunications interference (see the section titled "New Astrophysical Windows and Cosmic Mysteries" in Chapter 5).
3. **Using gravitational lensing to search for hypothetical black holes outside galaxies**. Deep subarc-second imaging of high-redshift objects to search for gravitational lensing may be the only way to find supermassive black holes outside the cores of galaxies. If the high-redshift objects are targeted, this search could be undertaken with an adaptive-optics system on a ground-based telescope. The wider field of view accessible from space, however, provides a special opportunity for serendipitous discovery.

To answer key questions relating to quasar power sources, it will be necessary to accomplish the following:

4. **Exploring the regions immediately surrounding black hole event horizons**. X-ray lines distorted by general relativity provide astronomers' only access to the black hole event horizon. To exploit this information, an x-ray telescope with 100 times the collecting area of AXAF and good angular resolution (preferably approaching that of AXAF) is needed to remove spectral contamination from other sources when the target quasars are moderately faint. New x-ray optics technologies that promise to achieve large collecting area and good angular resolution at reasonable cost need to be pursued.
5. **Understanding accretion and outflow processes associated with disks and jets**. Observers can indirectly make images of the interior regions of quasars with reverberation-mapping techniques using data obtained simultaneously at multiple wavelengths. X-ray information is especially critical and will be available with limited collecting area from AXAF, Astro-E, and XMM. HST and SIRTF will extend the spectrum of the peak power-emitting regions in quasar jets and in the powerful central continuum source. Simultaneous ultraviolet/x-ray and infrared/ultraviolet reverberation maps the larger-scale accretion disk regions. Quasar jets can be "imaged" with simultaneous gamma-ray/x-ray/ultraviolet/optical monitoring, as could be done by a successor to EGRET with multiwavelength capability, specifically, on-board x-ray and optical/ultraviolet monitors. Ground-based TeV Cerenkov telescopes would be a highly cost-effective adjunct to this experiment. Optical/ultraviolet variations caused by gravitational microlensing offer another route to mapping out the accretion disk.

Direct mapping of accretion disks the size of the solar system (10 AU) at the distance of the nearest giant galaxies (10 Mpc) requires an angular resolution of 1-microarc sec; this sets the long-term goal. In the radio band, interferometric imaging of bright quasar cores at the 10-microarc sec level can be demonstrated with current technology (e.g., VSOP). With further development, such interferometric imaging can also be accomplished in the infrared, visible, ultraviolet, and possibly even x-ray bands. In addition, next-generation space-based VLBI experiments, with enhanced sensitivity and frequency coverage, will explore jet structure and maser lines at resolutions of some 10-microarc sec.

6. **Placing the active nucleus in the context of the host galaxy**. Spectroscopy at moderate spectral and high angular resolution can map the kinematic field of the surrounding gas and stars. For nearby (redshift <0.04) active or dormant nuclei, near-infrared ground-based spectroscopy of the CO lines at 2.3 μm, coupled with adaptive optics, will be an extremely powerful tool. Spectroscopy from space is necessary to apply this technique at higher redshifts.

A separate approach would use thousands of channels of radio spectroscopy with the Green Bank Telescope (GBT), VLA, and VLBA, which will allow sensitive searches for lines diagnostic of cool gas. A small, multi-wavelength (ultraviolet/x-ray) mission could map hotter matter in the cores of active galactic nuclei.

CONCLUSIONS

As detailed above, astronomers have an emerging picture for the origins of structures on scales ranging from those of clusters of galaxies to the compact, active nuclei found in individual galaxies. This evolutionary picture needs a firm empirical framework, for which there are exciting and realizable prospects in future space missions. TGSAA's priorities for the study of galaxies and stellar systems are, in rank order (but with items 2 and 3 of equal priority), as follows:

1. **Detail the processes at work in the high-redshift universe by conducting a census of the universe as it was 1 billion years after the big bang**. Such a census would identify the ancestors of the familiar structures observers see relatively nearby—the gaseous precursors of galaxies, the earliest star-forming regions in galaxies, and the quasars at the highest redshift.

   Searches for these widely different astrophysical objects naturally require widely different observational techniques and capabilities. For example, the near-infrared spectral range is critically important because the energy from starlight in galaxies at high redshift peaks there, and the noise background is low in space. Angular resolution of 0.1 arc sec or better is required to detect faint point sources, avoid source confusion, and study structure in distant galaxies. Likewise, x rays are an integral part of the census, for they can tell us of the earliest massive condensations and the formation epoch of quasars. Much of the starlight may be reprocessed by gas and dust in forming galaxies. Detecting such systems and studying their constituents at any redshift require high sensitivity at submillimeter wavelengths for both line and continuum radiation. At all wavelengths significant increases in collecting area can yield significant increases in knowledge, both through increased spatial resolution and increased spectroscopic sensitivity.
2. **Link the high-redshift objects to their descendants by following the evolution to lower redshift, and undertake a detailed study of the underlying physical processes**. In particular, the dynamical, structural, and chemical evolution of the various structures are all fundamental and need to be pursued. Opportunities include mapping the temperature distribution, kinematics, and chemical composition of x-ray-emitting gas in clusters, and detecting weak absorption lines at high spectral resolution at ultraviolet wavelengths.
3. **Understand the formation and evolution of supermassive black holes in the nuclei of galaxies, and elucidate the processes at work there** . Of particular interest is the physics of matter in extremely high gravitational fields near the black hole event horizon. The most promising approaches include measuring changes in x-ray line profiles, since these lines may be formed close to the horizon and may allow mapping of the space-time metric. A greatly increased aperture is needed to collect enough x rays for fully time-resolved reverberation mapping, which also requires simultaneous multiwavelength measurements over a wide spectral range.

5

Cosmology and Fundamental Physics

The hot big bang cosmological model derived from Einstein's general theory of relativity provides a framework for understanding the evolution of the universe from a fraction of a second after its creation until the present, some 13 billion years later. The success of this model is an impressive confirmation of our present understanding of physics, including general relativity itself. In recent years, dramatic and accelerating progress has been evident in researchers' pursuit of the central goal of cosmological research—an understanding of the evolution and content of the universe. Such understanding rests on knowledge of fundamental physics, which often can be tested and extended only by observation of phenomena in extreme conditions in the cosmos. The current rapid progress in this field is owing in large part to access to space-based observations throughout the electromagnetic spectrum.

KEY THEMES

Cosmology and fundamental physics cover a diversity of phenomena whose spatial and temporal scales and characteristic energies range from the very large to the very small. In summarizing the main areas relevant to space astronomy and astrophysics, this chapter focuses on the following themes:

- Origin and evolution of the universe;
- Contents of the universe; and
- New astrophysical windows and cosmic mysteries.

ORIGIN AND EVOLUTION OF THE UNIVERSE

According to the big bang model, the universe began as a hot, formless sea of quarks and other fundamental particles of nature. As the universe expanded, it cooled. Quarks combined to create neutrons and protons. Sometime later, neutrons and protons combined to form the nuclei of the simplest elements. Eventually, atoms formed and accumulated via gravity into the objects seen by astronomers today—stars, galaxies, quasars, clusters of galaxies, superclusters, and filaments of galaxies such as the Great Wall (Figure 5.1). Four important areas for study that will test and enrich our understanding of this model can be identified.

1. *Cosmic microwave background*. The cosmic microwave background radiation (CMBR), which fills the universe and whose spectrum is precisely that of an object at a temperature of 2.73 K, is hard evidence that the universe was very hot and very dense in the beginning. It provides a snapshot of the universe in its infancy, a few hundred thousand years after the big bang. The intensity of the CMBR is nearly uniform across the sky, demonstrating that in the beginning the distribution of matter and radiation in the universe was astonishingly smooth. Small variations, amounting to about 0.001%, are now observed and indicate that the initial distribution of matter was slightly lumpy. This lumpiness, or inhomogeneity, was amplified by the action of gravity over billions of years to create ultimately all the structure seen in the universe today.
2. *Light elements*. Further evidence for an explosive beginning to the universe comes from the abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li. According to the hot big bang model these elements were produced by nuclear reactions when the universe was only a few seconds old. Their abundances in the atmospheres of old stars, interstellar clouds, and extremely metal-poor galaxies, thought to be the best contemporary samples of the early universe, provided the earliest confirmation of the hot big bang model.
3. *Hubble constant*. Theory predicts that the light from distant galaxies should be red-shifted in accord with Hubble's law; that is, redshift is proportional to distance. The measured redshifts of thousands of galaxies confirm this prediction. The light that astronomers now see was emitted by the most distant of these galaxies when the universe was one-sixth its present size and only a few billion years old. The expansion rate of the universe (quantified by the Hubble constant) indicates a beginning between 10 billion and 15 billion years ago. Current best estimates of the ages of the oldest stars are at the top of this range or even slightly beyond, but, obviously, the stars must be younger than the age of the universe itself. It is hoped that work during the coming decade will resolve this apparent contradiction.
4. *Inflation*. The hot big bang model also provides a foundation for discussing earlier times and addressing some of the most fundamental questions in the natural sciences. The high temperatures and densities that existed during the earliest moments of creation constitute a bridge. between cosmology and the study of the fundamental particles and forces of nature. The theoretical unification of these particles and forces is one of the central goals of physics and is a key to unlocking the secrets of the earliest moments of creation. Conversely, the study of the universe may offer important clues about this hoped-for unification.

A remarkable idea arising from the connection between the microscopic and the macroscopic is inflation. According to this theory the universe did not initially expand in a uniform manner, but, rather, underwent an early burst of enormous expansion. This expansion, or inflation, was driven by a very unusual form of energy—the so-called false-vacuum energy. Inflation can explain why the CMBR has almost exactly the same intensity in every direction and why the density of matter in the universe is near the critical density—the value required for gravitational attraction to ultimately halt the universal expansion. Inflation theory also makes two striking predictions: first, most of the matter in the universe exists in a form different from the atoms that compose everything we see around us; Second, all structures observed today in the universe grew from subatomic, quantum fluctuations.

Key Questions About the Origin and Evolution of the Universe

The success of the hot big bang model has added urgency to some old questions and has also led to the formulation of newer, deeper ones. These important questions include the following:

Geometry of the Universe

- How big and how old is the universe?
- Is the time back to the big bang really consistent with the ages of the oldest objects in the universe?
- Is space curved?
- What is the ultimate fate of the universe?
- Is there a large-scale repulsive force, represented by the "cosmological constant," as originally suggested by Einstein?

Answering these simple, but profound, questions requires accurate measurements of the Hubble constant, H_0; the deceleration parameter, q_0; and the average density of matter in the universe.

Origin and Evolution of Structure

While researchers are now fairly confident that all structure—from the smallest galaxies to the great walls of galaxies seen in large-scale redshift surveys—grew from small, primeval inhomogeneities in the distribution of matter, fundamental questions such as the following remain:

- What are the nature and the origin of the primeval inhomogeneities?
- How and when did the structure evolve?
- When were the first galaxies formed?

Origin of the Universe

The study of the unification of the forces of nature allows a scientific approach to addressing questions concerning the beginning of the universe itself. Key questions in this area include the following:

- What launched the expansion of the universe?
- What is the origin of the cosmic microwave background radiation?
- Were there other big bangs?

Recent Progress in Understanding the Origin and Evolution of the Universe

Observations by NASA's Cosmic Background Explorer (COBE) satellite have led to major advances in current understanding of the most important cosmological fossil, the CMBR. COBE measured its temperature to four significant digits—it is 2.728 ± 0.002 K—and showed that it is the most perfect black body ever studied. These findings established beyond any doubt that the CMBR is the "echo" of the big bang. By mapping the dipolar variation in the CMBR's temperature across the sky, COBE determined Earth's velocity with respect to the cosmic rest frame to a precision of 1%.

COBE also detected small variations (about 0.001%) in the intensity of the CMBR coming from different directions separated by angles of about 10 degrees and larger (Figure 5.2). This discovery provided the first evidence for the primeval lumpiness that under gravitational attraction grew into all the structure seen today, and it represented the first step toward establishing that all structure arose from subatomic quantum fluctuations. Since the COBE discovery, more than 10 other experiments, some ground-based, others on balloons, have also detected variations in the intensity of the CMBR. These measurements have confirmed the COBE result and are beginning to map out the inhomogeneities in the distribution of matter that gave rise to present structure.

Knowledge of the distribution of galaxies today is important to understanding the development of structure in the universe. The distribution of galaxies across the sky is readily found by classical astronomical techniques. To obtain the third dimension—distance from Earth—galaxy redshifts must be measured. Several large redshift surveys have been carried out, including one based on galaxies cataloged by the Infrared Astronomical Satellite (IRAS). The IRAS catalog is especially useful because it covers the entire sky (other catalogs miss much of the sky due to absorption of visible light by interstellar dust in our own galaxy, the Milky Way). All-sky coverage has allowed the mean mass density of a very large sample of the universe to be measured: based on a comparison of the distribution of IRAS-cataloged galaxies with Earth's velocity as determined by COBE, the average density was determined to be at least 30% and possibly as high as 100% of the critical density.

Significant progress has been made toward the goal of determining H_0 and q_0. The discovery and study of Cepheid variable stars in galaxies in the Virgo cluster and in the Fornax and Leo groups by several teams using the Hubble Space Telescope (HST) represented a major step in the process of calibrating bright, so-called secondary indicators that can be seen at great distances (e.g., supernovae and bright spiral and elliptical galaxies). In addition, new determinations of H_0 were made by physically based methods. Techniques of this kind include measurements of the temperature dip in the CMBR associated with hot, x-ray-emitting gas in clusters (the so-called Sunyaev-Zeldovich effect) and of the time delay associated with distant gravitational lenses. A reliable determination of H_0 is now within sight. Very distant supernovae have recently been discovered, providing important means toward a determination of the deceleration parameter.

HST and the Keck 10-meter telescope on Mauna Kea have opened new windows to the distant universe. HST has provided the deepest images of the universe ever, revealing galaxies and clusters apparently in the process of formation. The Keck telescope has provided a measurement of the temperature of the universe at a much earlier time, confirming a fundamental aspect of the big bang model—that the temperature of the universe decreases as it expands—and is providing the means to measure the abundance of deuterium in very old hydrogen clouds to compare with predictions of the big bang model.

Future Directions for Understanding the Origin and Evolution of the Universe

Cosmologists anticipate major advances in their understanding of the origin and evolution of the universe. Achievement of the 80-year-old quest to determine the geometry of the universe—that is, its structure on the largest possible scale—is now within reach. Moreover, bold ideas that can extend current knowledge to within the tiniest fraction of a second of the beginning are ready for testing. Thus, not only will researchers' understanding of the universe be greatly advanced, but light will also be shed on the unification of the fundamental forces and particles of nature. The key to achieving these goals is precise cosmological measurements. The most important future directions for study include the following, in generally decreasing order of priority:

1. **Determining the geometry of the universe**. The values of the Hubble constant, the deceleration parameter, and Einstein's cosmological constant, which determine the geometry of the universe, are notoriously difficult to measure. Thus a variety of approaches are needed. Observers are fortunate in having a powerful new tool for such measurements—high-angular-resolution mapping, on scales of a few arc minutes and larger, of the anisotropy of the CMBR. The CMBR is crucially important because it offers a snapshot of the universe at a simpler time, long before stars, galaxies, and other structures existed, and there are very precise predictions for the anisotropy expected for different values of the cosmological parameters. Such mapping will reveal the inhomogeneity in the distribution of matter that seeded all the structure seen today. Realizing the full implications of the variations in the CMBR will require a variety of ground- and space-based observations. Nonetheless, the scientific return clearly justifies the effort: rarely have theory and technology been better matched to address a major scientific question.

   Comparison between cosmological parameters determined from the CMBR and those measured by other techniques will provide vital tests of astronomers' current understanding about the geometry of the universe, and could reveal additional information. Astronomers will soon be able to determine the value of the Hubble constant to within 10% by using HST observations of bright secondary distance indicators. As mentioned, promising additional approaches include measurement of the Sunyaev-Zeldovich effect and measurement of the time delay associated with distant gravitational lenses; study of the motion of distant radio jets may also contribute. Ground-and space-based studies of distant supernovae may allow determination of the deceleration parameter and the cosmological constant.
2. **Testing models of the origin and evolution of structure in the universe**. Maps of the anisotropy of the CMBR can also test specific predictions of inflation theory (e.g., regarding the flatness of the universe, the specific pattern of the anisotropy, and the existence of exotic dark matter) and will test the most detailed model of how large-scale structure evolved, that is, the cold dark matter hypothesis. More generally, these maps will provide the basic data needed to test any alternative models of the early universe. They will allow determination of the total density of the universe and the density of ordinary matter to a precision of 5% or better. A comparison of the inhomogeneity that existed a few hundred thousand years after the beginning, as shown in maps of the CMBR's anisotropy, with that which exists today, as revealed in the large-scale redshift surveys (see Figure 5.1) now under

way (e.g., the Sloan Digital Sky Survey at Apache Point Observatory and the Two-Degree Field Survey at the Anglo-Australian Observatory), will be crucial to understanding how structure formed in the universe.

3. **Measuring the polarization of the cosmic microwave background radiation**. Some polarization of the CMBR is expected; if found it will offer an important test of current understanding of the origin of structure. Observations of polarization may also enable researchers to determine the epoch of primordial star formation.
4. **Searching for deviations from a blackbody cosmic microwave background radiation spectrum at radio wavelengths**. Such studies offer a unique window on exotic processes (e.g., decays of relic elementary particles) that might have occurred at early times.
5. **Measuring the anisotropy of the x-ray background radiation**. Studies of this type would provide a fundamental cosmological test, because the x-ray background comes largely from very distant galaxies. Its dipolar anisotropy should, therefore, coincide with the anisotropy of the microwave dipole, because matter averaged on a large scale should be at rest with respect to the CMBR.

CONTENTS OF THE UNIVERSE

Some of the most fundamental questions researchers ask concern the contents of the universe. Four significant facts seem secure:

1. *Outnumbering of atoms by photons*. Most of the known particles in the universe are the photons of the CMBR. The ultimate origin of these photons, which outnumber atoms by more than a billion to one, is unknown. Other photons of more recent origin—those of the infrared, x-ray, and gamma-ray backgrounds—pervade the universe; these photons were produced by distant stars, galaxies, and clusters long ago, and, although they are far fewer in number than the photons of the CMBR, they provide important clues about the formation of the objects from which they come.
2. *Absence of antimatter*. In an enormously large region around Earth, the universe is made of matter—and not of an equal mixture of matter and antimatter. This imbalance is extremely puzzling since both matter and antimatter are predicted to have been almost equally abundant at the beginning. Because photons so greatly outnumber atoms, the general absence of antimatter today suggests that the amount of matter and antimatter present at early times was unequal by one part in a billion. It seems likely that this difference in abundance is linked to a slight asymmetry in the laws of particle physics favoring the creation of matter rather than antimatter.
3. *Abundances of light elements*. The cosmic abundances of the light elements, D, ^{3}He, ^{4}He, and Li, are generally in accord with those expected based on calculations of their production during the first few minutes after the big bang. Further, the relative abundances give astronomers their most precise estimate of the amount of ordinary (baryonic) matter—about 5% of the critical density. Astronomers now know that only a fraction of ordinary matter has found its way into stars; most of the baryons may exist in the hot gas that permeates clusters of galaxies and intergalactic space.
4. *Existence of dark matter*. As already emphasized, most of the mass in the universe is dark, neither emitting nor absorbing any form of electromagnetic radiation. Known to exist only by its gravitational influence, it is present on all scales: in galaxies, in clusters of galaxies, and, perhaps, in even larger concentrations of mass such as the so-called Great Attractor. Although the total amount of dark matter is still unknown, good evidence indicates that there is more dark matter than can be accounted for as ordinary matter. If it is dominant, dark matter must have determined how structure formed in the universe, and it will determine whether or not the universe expands forever.

Key Questions About the Contents of the Universe

Dark Matter

Constructing a complete cosmology is impossible without a better understanding of dark matter, the dominant form of matter in the universe. Questions researchers need to answer include the following:

- What is the composition and what is the quantity of dark matter?
- How much of the universe is composed of ordinary matter, and how much exists in more exotic forms?
- What are the constituents of the exotic dark matter?
- How is the dark matter distributed?

Ordinary Matter

The history of ordinary matter is crucial to constructing a complete cosmology. Questions researchers need to answer include the following:

- In what form does ordinary matter exist today?
- How has the distribution of baryons changed over time—from primeval plasma to stars, hot gas in clusters of galaxies, warm gas between clusters, dead stars, and other forms that exist today?

Matter and Antimatter

Although particle physics provides a general framework for understanding the origin of the asymmetry between matter and antimatter, a detailed explanation remains to be found and tested. Astronomers still do not have a good answer to the following basic question:

- Why is the universe made of matter and not of both matter and antimatter?

Other Constituents

The photons of the CMBR remained unknown until 1964. Possible other undiscovered constituents include superheavy magnetic monopolies, cosmic strings, and the tiny, exploding primordial black holes predicted by Stephen Hawking. Thus, a basic question still to be answered is this:

- Are there radically new constituents of the universe that have yet to be discovered?

Recent Developments in Understanding the Contents of the Universe

In addition to greatly improving current knowledge of the CMBR, data from COBE set important limits on the level of the cosmic infrared background radiation that is expected from the oldest stars and galaxies. Significant progress has also been made in understanding the extragalactic x-ray and gamma-ray background radiation. Measurements made by the Roentgensatellit (ROSAT), the Advanced Satellite for Cosmology and Astrophysics (ASCA), and the Compton Gamma-Ray Observatory (CGRO) indicate that active galaxies account for a large part—perhaps almost all—of these backgrounds.

Important advances in the understanding of dark matter include new estimates of the average density of matter based on comparing the spatial distribution of galaxies with galaxy velocities relative to the rest frame of the CMBR. As discussed above, these estimates strongly suggest that the density of matter is at least 30% of the critical density. One of the fundamental predictions of general relativity, the deflection of light by gravity, has been used to directly probe dark matter. Gravitational lensing of distant galaxies by intervening clusters has allowed the dark matter in the clusters to be mapped and weighed by both ground- and space-based observatories. Gravitational microlensing of stars in the nearest external galaxy, the Large Magellanic Cloud, has been Used to discover dark baryons in the form of so-called massive compact halo objects (MACHOs) in the halo of the Milky Way. MACHOs may represent a new population of objects and may constitute between 10% and nearly 100% of the mass of the Milky Way's halo.

X-ray telescopes such as ROSAT and ASCA have provided important information about the gas in galaxy clusters, showing that it represents between 10% and 20% of the total mass. The implications of this work are twofold. First, most and perhaps all of the "dark" baryons in clusters exist in the form of hot gas. Second, the bulk of the matter in clusters is still of unknown composition. The hot gas appears to be the main repository of baryons in the universe today. The x-ray observations of clusters, which probe the amplitude of mass fluctuations, have been an important complement to galaxy redshift surveys, which Probe the amplitude of the fluctuations in galaxy numbers.

The most accurate determination of the abundance of ordinary matter, between 1% and 10% of the critical density, comes from measuring the cosmic abundance of D, ^{3}He, ^{4}He, and Li, the light elements synthesized a few seconds after the big bang. Systematic progress has been made toward determining the abundances of all four in samples of primordial matter that have not been significantly altered by stellar nuclear processes.

Observational evidence strongly suggests that most of the dark matter is not ordinary matter. In particular, the average density of the universe appears to be significantly higher than the baryonic density inferred from the cosmic abundances of the light elements. Moreover, it is difficult to construct a consistent cosmology with only baryons. Dark matter in the form of relic elementary particles provides the most natural explanation for the development of the structures seen today as the primeval matter inhomogeneities inferred from measurements of the CMBR's anisotropy.

In the past 5 years, ultrasensitive ground-based experiments have begun to search for yet undetected elementary particles that might constitute the dark matter in the halo of the Milky Way. Experiments are under way or under development to search for the hypothetical axon and neutralino. The properties of known particles that could contribute to the dark matter also continue to be investigated. If one of the three neutrino species has a mass between 2 eV and 30 eV, then some or all of the dark matter may be in the form of neutrinos produced in the big bang. A variety of experiments are searching for evidence of neutrino mass. There are hints from solar-neutrino experiments and an accelerator experiment that at least one neutrino species has mass.

Future Directions for Understanding the Contents of the Universe

Future directions for studies of the contents of the universe include the following, in no particular order:

1. **Undertaking a multifaceted study of the amount, nature, and distribution of dark matter**. Characterization of dark matter is one of the most important problems in all of astrophysics, and many opportunities exist for significant advances. A number of new approaches for measuring the mean mass density of the universe, e.g., high-resolution mapping of the CMBR, could be used to determine the total amount of dark matter. Microlensing is an important new probe of baryonic dark matter; a small, space-based telescope operating in conjunction with existing ground-based telescopes could reveal much about the nature of the MACHOs discovered in the Milky Way's halo. More remains to be learned about the distribution of baryons and dark matter in clusters of galaxies from higher-resolution x-ray observations. Likewise, gravitational lensing could be used to probe directly the distribution of dark matter in clusters and in the halos of large spiral galaxies, and it might be used to search for concentrations of dark matter that are not associated with bright galaxies. Ground-based experiments will continue to search directly for the elementary particles that contribute to the Milky Way's halo. The search for positrons, gamma rays, and antiprotons from dark-matter annihilations in the halo of the Milky Way is an important complementary approach that could provide the first direct evidence for nonbaryonic dark matter.
2. **Determining the primeval abundances of the elements created in the big bang**. Definitive measurement of the abundance of deuterium is a key test of primordial nucleosynthesis that might also pin down the density of ordinary matter to a precision of 10% or better. The Far-Ultraviolet Spectroscopic Explorer can be used to determine precisely the cosmic helium abundance. Other opportunities for more accurately determining the abundances of the light elements merit pursuit.
3. **Investigating the infrared, ultraviolet, x-ray, and gamma-ray background radiation**. Space-based observations of these backgrounds, which were produced in part by stars and galaxies in their infancy, offer a window on the origin and evolution of stars and galaxies.
4. **Remaining alert to unexpected discoveries**. It is important to be on the lookout for entirely new phenomena. The discovery of the most important cosmological relic, the cosmic microwave background radia

tion, was serendipitous. The discovery of a single antihelium nucleus, a magnetic monopole, or an exploding, primordial black hole would profoundly change cosmology and might have implications for the unification of the particles and forces of nature.

NEW ASTROPHYSICAL WINDOWS AND COSMIC MYSTERIES

Astronomy is replete with examples of significant advances or astounding discoveries arising from the opening of new observational windows. Much of the bedrock of modern astronomy—infrared, radio, x-ray, and gamma-ray astronomy—grew out of exploitation of such windows. Several promising and exciting new windows are either now accessible or on the verge of being so. In addition, some well-explored windows present seemingly intractable mysteries. Current understanding singles out four important areas ripe for progress:

1. *Gravitational radiation*. The emission of gravitational radiation by accelerating masses is a crucial prediction of general relativity. Gravitational waves offer a promising new tool for observing the behavior of astronomical systems under conditions of strongly nonlinear gravity and superhigh velocities.
2. *Low-frequency radio waves*. This window, spanning the spectral band from about 30 kHz to 30 MHz, is the last important region of the electromagnetic spectrum that is still largely unexplored. Space-based observations are essential because such radio waves are generally unable to penetrate Earth's ionosphere. Many important astrophysical questions concerning the solar system, the galaxy, and the distant universe can be addressed by low-frequency radio observations with angular resolution near an arc minute.
3. *Gamma-ray bursts*. The nature and origin of gamma-ray bursts present one of the deepest mysteries in contemporary astrophysics. Celestial gamma-ray bursts were discovered serendipitously several decades ago by U.S. satellites designed to detect clandestine nuclear tests, and well over 1,000 have been detected subsequently by scientific satellites, chiefly CGRO. Yet until very recently none have been located with enough precision to enable identification with known astronomical objects. Possible explanations of the mysterious objects range from coalescing neutron stars and black holes at cosmological distances, to magnetic flares on the surfaces of neutron stars in large galactic halos.
4. *Ultrahigh-energy cosmic rays*. These particles, with energies in excess of some 10^{19} eV, open a promising window onto astrophysical processes, cosmology, and fundamental physics. Because their deflection and containment by galactic magnetic fields are negligible, particles with such energies must be extragalactic, and yet they are so energetic that they are blocked by interactions with the photons composing the CMBR within a few hundred megaparsecs, a distance that is small compared to the size of the universe. Their existence could signal new physics associated with grand unified theories of particle physics.

Key Questions About New Astrophysical Windows and Cosmic Mysteries

Often in astronomy, the opening of new observational windows has led to such novel discoveries that the relevant questions could not have been conceived beforehand. For unexplored territory such as the low-frequency radio band, it is difficult to anticipate what will be found, or even to formulate the right questions to ask. For other new windows and for unexplained observations in already-explored windows, the task of formulating key questions is somewhat easier. These include the following:

Gravitational Waves

- What are the characteristics of gravitational waves as predicted by general relativity?
- What could gravitational waves reveal about dynamical processes in the universe involving high speeds and strong gravity?
- Are there supermassive black holes in the centers of galaxies and quasars?
- How do supermassive black holes form, merge, and swallow up stars?

Gamma-Ray Bursts

- How can the recent discovery of a soft x-ray afterglow and a fading optical emission coincident with a gamma-ray burst constrain burst models?
- Are gamma-ray bursts located within the Milky Way's halo, or at cosmological distances?
- What is the nature of the processes responsible for the sudden, enormous energy releases of gamma-ray bursts and how do they compare with the relatively nearby soft gamma-ray repeaters in the galactic disk? This question is of particular significance if gamma-ray bursts occur at cosmological distances.
- What, if anything, can gamma-ray bursts reveal about the early universe?

Ultrahigh-Energy Cosmic Rays

- What is the origin of cosmic rays with energies above 10^{19} eV?
- Do these particles reveal more about cosmology or about new physics?

Recent Developments in Understanding New Windows and Cosmic Mysteries

The construction of a network of ground-based, kilometer-scale, laser-interferometric gravitational wave observatories in the United States and Europe (the LIGO and VIRGO projects, respectively) began in the past decade, with the first observations planned for 2000-2001. These instruments will be most sensitive to gravitational waves in the 10- to 500-Hz band and will be capable of detecting the final orbital decay and coalescence of binary systems containing neutron stars or black holes at cosmological distances. Also detectable will be supernovae within a few hundred megaparsecs and possibly a cosmological background of gravity waves.

Cosmic gamma-ray bursts are distributed very uniformly over the sky, and their distribution of peak intensities shows that most of the sources cannot reside within the galactic disk. Rather, the sources must occupy either an extended, spherically symmetric region such as an extremely large galactic halo or a cosmologically distant region of the universe. Possible observation of temporal stretching in the duration of faint gamma-ray bursts is suggestive of cosmological time dilation. If so, the sources must be located at redshifts of $z \sim 1$ to 2. If the sources are truly so remote and if they emit isotropically, then their energy output in gamma rays alone in less than a minute is comparable to the total energy radiated by a supernova. If the sources are this distant, they could potentially be a unique tool for investigating a new fundamental phenomenon widespread throughout the universe. If not at cosmological distances, gamma-ray bursts may be the only observable manifestation of some unseen matter in a highly extended halo about our own galaxy. The recent discovery of the apparent repetition of a "classical" gamma-ray burst over a period of several days would require either gravitational lensing of an object at a cosmological distance (although differences in burst profile make this unlikely) or a source in the galactic halo. Indeed, the latter explanation may suggest that gamma-ray bursts are somehow related to the distinctly different population of so-called soft gamma-ray repeaters in the galactic disk. Recent precise positions for two soft gamma-ray repeaters and the identification of one with a persistent x-ray source strongly suggest that they are associated with supernova remnants and thus, presumably, neutron stars. However, the remarkable recent discovery by the Satellite per Astronomia in Raggi X (SAX) of the soft x-ray afterglow of a "classical" gamma-ray burst, subsequently identified with a fading optical source, points the way to possible identification of gamma-ray bursts: rapid follow-up observations at soft x-ray and optical wavelengths of bursts located to within an accuracy of a few arc minutes or better.

A cosmic ray air shower generated by a primary particle with energy as high as 3×10^{20} eV (48 joules), the highest-energy particle event yet found in nature, has recently been detected by the Fly's Eye detector in Utah. If the primary particle is cosmological in origin, then the inferred energy exceeds a bound imposed by interaction with the CMBR. Although a number of objects have been considered as possible sources, no plausible object has been found within 50 Mpc in the direction of the detected event. Possible resolutions of this mystery include the existence of a hitherto unknown particle with very low interaction with the CMBR, but with sufficient interactions with matter to produce the observed air showers.

Future Directions for Understanding New Astrophysical Windows and Cosmic Mysteries

Priority directions for the study of new windows and cosmic mysteries include, in generally decreasing priority order, the following:

1. **Searching for low-frequency gravitational waves**. In the frequency band between 10^{-4} and 10^{-1} Hz, known or predicted sources of gravitational waves include binary systems of normal stars, white dwarfs or neutron stars in the Milky Way, formation or coalescence of massive black holes in galactic nuclei, and a cosmological background of waves. Observation of massive black hole mergers offers the opportunity to map the space-time structure in the vicinity of a black hole and thereby to test general relativity in a strong-field regime. Discovery and study of such massive black hole processes could also have a strong impact on theories of galactic structure and evolution. Because of seismic and gravity-gradient noise on Earth, searches for gravitational waves at frequencies lower than 10 Hz must be done in space.
2. **Testing the foundations of general relativity**. Testing of the principles of general relativity, which underlies current theories of cosmology and gravitational radiation, is critically important. The principle of equivalence, one of the foundations of modern physics, asserts the equivalence of uniform acceleration and a uniform gravitational field. A critical test of this principle involves demonstrating whether the ratio of inertial mass to gravitational mass is the same for two different types of material. The best ground-based measurements, performed several decades ago, verified this equality to an accuracy of a few parts per trillion. A proposed space-based experiment could increase the sensitivity of this test by a factor of about 100,000.
3. **Increasing the number of known gamma-ray burst sources and improving knowledge of their precise locations**. Over the next decade it is very likely that key questions of the distance scale of gamma-ray bursts can be answered by rapid follow-up observations of moderately well known (accurate to ± a few arc minutes) burst locations at soft x-ray and optical wavelengths, as has recently occurred. Another approach is to obtain accurate (± arc seconds) burst locations using gamma-ray burst detectors widely dispersed in the solar system or by using improved wide-field hard x-ray imaging detectors. A small sample of gamma-ray burst sources identified with host galaxies would point strongly to the cosmological model. A sensitivity test of halo models could be made by imaging and monitoring the halo of M31 in hard x rays. Understanding of the nature of the sources can be advanced by multiwavelength detections and by sensitive high-resolution spectra of gamma-ray bursts in the entire band from hard x rays to gamma rays.
4. **Determining the origin of the ultrahigh-energy cosmic rays**. Assessment requires improved data on the incident direction, mass, and energy of these events. Current indications of a correlation of events with the supergalactic plane will require much more air-shower data for confirmation. Substantial progress will be enabled by the planned international 5,000-sq.-km Pierre Auger Array. This facility, with elements in the United States and Argentina, will allow an order-of-magnitude increase in exposure. A complementary experiment would involve an orbiting platform observing scintillations caused by air showers induced by cosmic rays from above the atmosphere.
5. **Exploring the low-frequency radio window**. Observations from space are required, because from Earth's surface, observations at low radio frequencies are blocked by the ionosphere. In this window observers may find new sources of coherent emission, new classes of very steep spectrum sources, and "fossil" radio galaxies. Studies of the low-frequency spectra of galactic supernova remnants, pulsars, and the extended galactic nonthermal radiation will address questions concerning particle acceleration mechanisms, magnetic field strengths, and radiative lifetimes. The distribution of low-energy cosmic rays and diffuse ionized hydrogen in the Milky Way can be determined. Measurements of the angular broadening of extragalactic sources caused by interstellar scattering will provide data on the distribution and turbulent structure of the interstellar plasma. But the real excitement will be in exploring the new territory below 30 MHz, which is likely to uncover new phenomena.

CONCLUSIONS

Taking into consideration the subjects discussed above, TGSAA identified the following scientific opportunities as the highest priorities for space research in cosmology and fundamental physics during the next 5 to 10 years. They are listed from highest to lowest priority.

1. **Determine the geometry of the universe by measuring the anisotropy of the cosmic microwave background radiation.** High-precision mapping over the full sky provides a powerful new technique for accurate determination of long-sought cosmological parameters. Comparison with improved results from classical astronomical techniques and other methods will provide a firm basis for refining cosmological models.
2. **Test theories for the origin and evolution of structure in the universe.** Measurements of the primordial matter inhomogeneities revealed by maps of the cosmic microwave background radiation, when combined with measurements of the large-scale distribution of matter today, will test the currently favored theories of structure formation, inflation, and cold dark matter. Such data will also provide the observational facts needed to test alternative theories.
3. **Determine the amount, distribution, and nature of dark matter.** Many types of measurements can contribute to resolution of the questions concerning dark matter. Among these are mapping of the anisotropy of the cosmic microwave background radiation, study of gravitational lensing by objects ranging from MACHOs to distant galaxy clusters, measurement of the hot, x-ray-emitting gas in galaxy clusters, precise measurement of the primordial abundances of the light elements, and a direct search for new species of particles.

The following scientific opportunities are important, but of lower priority than those listed above. They are shown in priority order.

1. **Test predictions of general relativity in the strong-gravity regime.** By initiating observations of low-frequency gravitational waves, astronomers can probe the strong gravitational fields near massive black holes and so extend the conditions under which the predictions of general relativity can be tested. Such studies will also open a unique new window for the study of gravitational interactions in a variety of astrophysical systems.
2. **Investigate the nature of cosmic gamma-ray bursts and the origin of ultrahigh-energy cosmic rays.** While definitive approaches for resolving these mysteries are hard to specify, understanding of both is likely to be improved by detection of more events with improved directional information.
3. **Extend radio astronomy to ultralow frequencies.** Measurement of radio waves blocked by Earth's ionosphere will likely enhance understanding of familiar phenomena and reveal new ones.

6

Conclusions and Recommendations

The four preceding chapters describe in detail the great scientific progress that has occurred since 1991 on a broad range of astrophysical topics of interest to NASA. Among the many highlights, general-purpose instruments such as the Hubble Space Telescope (HST) and the Keck telescope have transformed astronomers' thinking about the distant universe and have provided remarkable evidence regarding the process of star formation in our own galaxy. The Cosmic Background Explorer (COBE) has provided stunning confirmation of the hot big bang cosmology, and it has found the long-sought primordial seeds of large-scale structure, providing a quantitative basis for theories of how structure evolved. The Compton Gamma-Ray Observatory (CGRO) has detected more than 1,000 gamma-ray burst events and has demonstrated that they are isotropically distributed on the sky, implying an origin outside the disk of our galaxy.

The signature of massive planets in orbit around a number of nearby stars has been detected by ground-based spectroscopy. The evidence for the existence of black holes in several x-ray binary systems now is quite solid, and the existence of giant black holes in the centers of several galaxies is now established beyond any reasonable doubt.

Astrophysics covers an enormous diversity of physical phenomena, but there is much cross-fertilization, and advances in one subfield are often crucial to advances in another. The existence of numerous important topics in astrophysics, ripe for further progress by judiciously selected NASA missions beyond those assumed in Chapter 1 (HST, CGRO, Advanced X-Ray Astrophysics Facility, Space Infrared Telescope Facility (SIRTF), Stratospheric Observatory for Infrared Astronomy (SOFIA), and Far-Ultraviolet Spectroscopic Explorer), presents extraordinary opportunities.

The research activities identified in the concluding sections of Chapters 2 through 5 are the foundation on which TGSAA's overall recommended priorities for space astronomy and astrophysics are based. The priorities recommended in Chapters 2 through 5 (Box 6.1) encompass highly diverse spatial, temporal, and energy scales, ranging from extrasolar planets to supermassive black holes, from the origin of the universe to its ultimate fate, and from submillimeter radiation emitted by forming stars to ultrahigh-energy cosmic rays of unknown origin. Some of the recommended priorities may be achieved with a limited series of observations, while others will require long-term, multifaceted observing programs. In setting its priorities, TGSAA made every effort to be realistic and to consider recent progress and the prospects for the requisite technology. After considerable productive discussion and debate, TGSAA was able to make a robust selection of a ranked list of scientific endeavors that are most compelling as the foci of NASA's mission planning over the next 5 to 10 years.

BOX 6.1 RECOMMENDED PRIORITY RESEARCH ACTIVITIES IDENTIFIED IN CHAPTERS 2 THROUGH 5

Planets, Star Formation, and the Interstellar Medium

- Obtain a census of planetary systems around enough stars (˜1,000) so that the frequency, separations, and masses of planets comparable to or larger than Uranus can be investigated for a range of types of stars and stellar systems.
- Characterize the very earliest stages of star formation by observing the structure and dynamics of protostellar regions.
- Determine the large-scale three-dimensional structure of the interstellar medium and the star-formation regions within it.
- Detect indirectly terrestrial-mass planets.
- Perform ultraviolet spectroscopic studies of the connection between galactic disks and halos with a sensitivity significantly higher than that now provided by the Hubble Space Telescope.
- Conduct near-infrared imaging and spectroscopic studies of young embedded star clusters.

Stars and Stellar Evolution

- Understand the origin and astrophysical manifestations of black holes.
- Study the behavior of matter at extremes of gravity, rotation, magnetic field, and energy density.
- Investigate fundamental issues concerning the origin of the elements.
- Improve understanding of stars as markers of the size and age of the universe.
- Understand the effects of rotation and magnetic fields, and the effects of binary companions.

Galaxies and Stellar Systems

- Detail the processes at work in the high-redshift universe by conducting a census of the universe as it was 1 billion years after the big bang.
- Link the high-redshift objects to their descendants by following the evolution to lower redshift, and undertake a detailed study of the underlying physical processes.
- Understand the formation and evolution of supermassive black holes in the nuclei of galaxies, and elucidate the processes at work there.

Cosmology and Fundamental Physics

- Determine the geometry of the universe by measuring the anisotropy of the cosmic microwave background radiation.
- Test theories for the origin and evolution of structure in the universe.
- Determine the amount, distribution, and nature of dark matter.
- Test predictions of general relativity in the strong-gravity regime.
- Investigate the nature of cosmic gamma-ray bursts and the origin of ultrahigh-energy cosmic rays.
- Extend radio astronomy to ultralow frequencies.

The scientific rationale for TGSAA's leading four recommended priorities is as follows:

1. **Determination of the geometry and content of the universe by measurement of the fine-scale anisotropy of the cosmic microwave background radiation** . The establishment of the hot big bang cosmology is, as explained in Chapter 5, one of the great scientific achievements of the twentieth century. The 80-year-old goal of

determining the geometry of the universe is now within reach. Bold and powerful ideas that can extend current knowledge to encompass events occurring within a tiny fraction of a second after the beginning can now be put to observational test.

Accomplishing this goal will not only greatly advance astronomers' understanding of the universe on the largest possible scale, but, paradoxically, at the other extreme of size will also shed light on the unification of the fundamental particles and forces of physics—an unprecedented marriage of science at the macroscopic and microscopic scale.

Determining the geometry of the universe requires precise measurements of three classic parameters: the Hubble constant (H_0), the deceleration parameter (q_0), and Einstein's cosmological constant (L). As a result of the recent discovery by COBE of minute variations in intensity, or ripples, in the cosmic microwave background radiation (CMBR), caused by small initial inhomogeneities in the distribution of matter in the early universe, astronomers now have a remarkably powerful new tool to determine these parameters. This tool is high-angular-resolution mapping, on scales of a few arc minutes and larger, of the anisotropy of the CMBR. The CMBR is fundamental to this effort because it offers a snapshot of the universe at a simpler time, long before stars, galaxies, and other structures existed. Moreover, there are very precise predictions for the anisotropy expected—specifically, the spectrum of the ripples as a function of size—as functions of the three cosmological parameters. Such measurements will provide maps of the inhomogeneities in the distribution of matter that seeded all the structure in the universe seen today, and they offer the promise of a determination of the fundamental cosmological parameters to a precision of 1 to 5%. High-resolution mapping of the CMBR will critically test the theory of inflation, specifically the predictions it makes that the universe is spatially flat (euclidian), that the spectrum of anisotropies has a specific form, and that a large quantity of dark matter exists. In addition, the mapping will test the cold dark matter theory, the most detailed picture currently available to explain how large-scale structure evolved.

Realizing the full potential of the measurements of the CMBR will require a multiplicity of approaches, both from space and from the ground. The anticipated scientific payoff clearly justifies the effort. Indeed, rarely have theory and technology been better matched to address a scientific question of such transcendent importance. That is the essential reason that TGSAA has placed the prime recommendation of its Panel on Cosmology and Fundamental Physics at the top of its list of overall recommended priorities.

2. **Investigation of galaxies near the time of their formation at very high redshift**. The powerful capabilities of the HST and the Keck 10-meter telescope have greatly expanded astronomers' knowledge of the distant universe, providing for the first time a direct look at the evolution of galaxies only a few billion years after the big bang. Understanding the origin of galaxies is, as explained in Chapter 4, central to astronomers' picture of how the universe around us came to be the way it is. Studies of the CMBR described above provide a direct glimpse of the condensations that eventually became galaxies and the structures seen by astronomers in the universe today. The birth of stars and galaxies is, however, very complex and still only poorly understood. Fortunately, astronomers can take advantage of the vast distances to galaxies. Because it can take billions of years for light to travel to us from distant objects, observers have the opportunity to look back in time and see galaxies as they were when their light was emitted billions of years ago, the era when galaxies themselves were born. While the Hubble and Keck telescopes have given observers a glimpse of the most luminous objects at a time a few billions years after the big bang, astronomers currently know very little about ordinary galaxies like the Milky Way at that epoch. Researchers cannot currently obtain spectroscopic information for most of the galaxies shown in the so-called Hubble Deep Field (see Figure 4.1). It is urgent that observers persist in this exploration and push out to even greater distances and earlier cosmic epochs. The next generation of space-based instrumentation, beginning with SIRTF, will have the technical capabilities to perform what is, in essence, the highest priority of TGSAA's Panel on Galaxies and Stellar Systems, that is, to trace out the whole process of galaxy formation, from the gaseous precursors of galaxies, through the earliest episodes of star formation, to the formation of supermassive black holes in the nuclei of galaxies.
3. **Detection and study of planets around nearby stars**. The recent discovery of planets around at least 10 nearby stars has, as explained in Chapter 2, opened a new chapter in astronomy and, not surprisingly, also generated great public interest. Observations to date suggest a great diversity among planetary systems, and in TGSAA's judgment, it would be premature to focus attention at this time on terrestrial planets. Nearly all the

planets detected are far more massive than Earth, having masses comparable to or greater than that of Jupiter. As a first step toward understanding extrasolar planets, it is essential to take a census of planetary systems around enough nearby stars (~1,000) to determine their characteristics as a function of the properties of their parent stars.

While ground-based measurements of radial velocities are suitable for detecting massive planets close to their parent star, high-precision astrometry at the level of 10-microarc sec or better is required to detect planets that are much smaller or more distant than those found so far. Space-based interferometry appears crucial for achieving this goal. This activity, the highest priority of the Panel on Planets, Star Formation, and the Interstellar Medium, is the first step in achieving the long-range goal of detecting and observing terrestrial planets around nearby stars.

4. **Measurement of the properties of black holes of all sizes**. Black holes, hypothetical objects of great scientific interest predicted by general relativity, are fascinating to scientists and the general public because of their bizarre properties. While the reality of black holes has long been questioned, they have now almost certainly been observed in a wide range of astronomical settings. As described in Chapter 3, observations over the past 5 years from x-ray satellites and ground-based radio and optical telescopes have established at least six very strong black hole candidates among the Milky Way's population of x-ray binary stars.

   Moreover, as explained in Chapter 4, observations with the HST and the Advanced Satellite for Cosmology and Astrophysics have also provided almost certain evidence for the existence of very much more massive black holes in the nuclei of remote active galaxies. These studies lend support to the hypothesis that accretion onto black holes is the fundamental explanation for the exceptional luminosity of quasars. Observations with the Very Long Baseline Array have obtained even more compelling evidence that the nuclei of the much more common, mildly "active" galaxies contain black holes with masses some 10 million times that of the Sun. As a result of these developments, there is general agreement that black holes have been detected over a wide range of masses.

   TGSAA concluded, based on the rankings given by its Panel on Stars and Stellar Evolution and Panel on Galaxies and Stellar Systems, that a systematic study of black holes, particularly at high energies, should be given high priority by NASA during the coming decade. Key issues to be addressed are the formation of black holes over the entire mass range observed; the mechanisms by which accretion onto black holes produces both a prodigious output of energy and jet-like outflows; the number of stellar-mass black holes in galaxies and galactic halos; and possible tests of the laws of physics in the extreme environment close to black holes.

   Each of the chapters contributed by TGSAA's panels describes a number of priority topics in addition to the four listed above. Some are more suitable than others for implementation by NASA missions in the coming decade. Continued NASA support for technology development is appropriate before a number of the others will be suitable for flight opportunities.

Many of these additional scientific priorities are best addressed by multifaceted studies, including additional theoretical investigations. A number of the topics discussed are possible scientific objectives for missions over the coming decade in NASA's ongoing Explorer-class satellites. Others might be best pursued by balloon-borne payloads, and still others are best suited to ground-based studies. TGSAA debated the merits of including an expanded list of recommended priorities and decided that the following four topics are particularly interesting and timely for NASA's consideration, addressing questions of fundamental significance. These additional recommended priorities, unranked, are as follows:

1. **Study of star formation by, for example, high-resolution far-infrared and submillimeter observations of protostars, protoplanetary disks, and outflows**. Chapter 2 explains that although star formation is a continual process in our galaxy, observing the creation of stars from interstellar material is a formidable challenge because these regions are inevitably deeply shrouded in thick clouds of dust. Astronomers' understanding of the process whereby dense clouds form individual young stars and their circumstellar disks is far from complete. Most stars are observed to form in clusters, but astronomers do not understand how this affects the properties of individual protostars. Nor do they understand the distribution of stellar masses, the most crucial factor determining the life history of stars. SIRTF and SOFIA will provide new insights into these questions, but future missions with higher spatial and spectral resolution will be needed.
2. **Study of the origin and evolution of the elements**. Chapter 3 describes how all the chemical elements on which life depends were produced in early generations of stars. These elements are subsequently expelled by

supernova blast waves or stellar winds back into the interstellar medium and are eventually incorporated into subsequent generations of stars. Astronomers understand the general mechanism of mass loss from stars, but they cannot explain why the material is ejected so anisotropically. The abundance of heavy elements is higher toward the centers of galaxies, as expected. Researchers have, however, no idea how the central regions of active galaxies (e.g., quasars), observed at high redshift, can produce a solar distribution of heavy elements so quickly.

The interior structure of the highly evolved stars that eventually eject their metals into space is quite complex. A key question that is poorly understood at present is how mass loss from, and mixing inside, stars affect stellar evolution and nucleosynthesis.

3. **Resolution of the mystery of the cosmic gamma-ray bursts**. Chapter 3 emphasizes that some of the most challenging problems in astrophysics remain in the exploration of the behavior of systems under extreme physical conditions associated with compact stars. Because of the large gravitational potential and extreme temperatures encountered, the natural form of radiation is in the x- or gamma-ray bands. Study of these high-energy emissions is done most efficiently from space. Perhaps the prime indication of the primitive nature of current understanding of compact objects is the inability of researchers to explain the mysterious gamma-ray bursts.

   Astronomers have, as described in Chapter 5, known of the existence of gamma-ray bursts for more than 20 years, but only recently have obtained fairly conclusive evidence that the bursts probably originate from outside the disk of our galaxy. The transient nature of the bursts makes it exceptionally difficult to identify a counterpart source in any other waveband. As a result, astronomers do not know the most fundamental property of the gamma-ray burst sources: their distance. Hence major questions are unresolved. Are they at cosmological distances or in an extended halo of our own galaxy? Is the radiation collimated by some sort of jet? Why is such a large fraction of the energy emitted at such a high energy? The recent discovery by the Satellite per Astronomia in Raggi X (SAX) of the soft x-ray afterglow of at least one gamma-ray burst, and the subsequent identification with a fading optical object, may point the way to resolving at least the distance-scale mystery of the gamma-ray bursts. However, detailed understanding of the bursts and their slowly fading counterparts at longer wavelengths (e.g., optical and soft x-ray) poses major challenges. Given the heavy obscuration expected in some galaxies, rapid infrared follow-up may be required to identify the objects and their underlying physics.
4. **Determination of the amount, distribution, and nature of dark matter in the universe**. The only direct evidence for dark matter derives, as discussed in Chapters 4 and 5, from astrophysical inference of gravitationally bound objects, such as galaxies and clusters of galaxies, but the evidence is ubiquitous and consistent numbers are measured by several very different techniques. Astronomers still have no idea whether this dark matter takes the form of a collection of compact dead stars or primordial black holes, a hitherto unseen elementary particle, or something even more exotic. Theories of elementary particle physics suggest several reasonable candidates for this dark matter, some of which might be detectable in terrestrial laboratory experiments. Continued study of dark matter on a variety of fronts is of critical importance to astrophysics.

Beyond this expanded list of scientific priorities, there are many additional unresolved scientific questions raised within the four chapters contributed by TGSAA' s panels. Questions that fall outside the scope of the eight priorities listed above are not necessarily of minor interest. Some are best addressed by ground-based programs or by level-of-effort activities such as the peer-selected Explorer missions. For others, the time scale for the required technology development is longer than practical for a mission scheduled for launch within the next decade. The most suitable approach for NASA to adopt to prevent these important scientific questions from being overlooked is to continue a vigorous program of research and analysis as well as theoretical studies throughout the coming decade. In addition, adequately funded technology-development programs will be necessary to answer many of the questions posed in Chapters 2 through 5. Examples include investment in the precision photometric techniques required for the search for extrasolar planets (Chapter 2) and in the development of large-format infrared detectors for the study of the high-redshift universe (Chapter 4). Since the members of TGSAA were selected mainly for their scientific expertise, many issues relating to the technological readiness of some of the priorities in this report were not considered in depth. Additional study by more appropriately constituted groups is thus needed before implementation of some of the present recommendations.

Glossary

ACS: Advanced Camera for Surveys— Instrument to be installed on Hubble Space Telescope in 1999 servicing mission. ACS consists of three cameras, covering the wavelength range from 120 to 1,000 nm.

AGN: Active galactic nuclei— The nuclei of certain galaxies harbor a compact, solar-system-sized object capable of outshining the rest of the galaxy by a factor of 100 or more. The ultimate energy source for active galaxies is now widely thought to be accretion of matter onto a massive black hole (see also *blazar* and *quasar*).

Air shower— Cascades of particles produced when highly energetic cosmic rays collide with atoms and molecules in Earth's upper atmosphere.

Annihilation radiation— The radiation produced when a particle and its antiparticle collide and destroy one another. In the case of collisions between electrons and positrons, gamma rays with a characteristic energy of 511 keV are produced.

ASCA: Advanced Satellite for Cosmology and Astrophysics— Low Earth-orbiting x-ray telescope designed to operate in the 0.3- to 12-keV bands. ASCA was launched by Japan in 1993.

Astro-E— Low Earth-orbiting x-ray telescope in the 0.4- to 10-keV range. Astro-E is to be launched by Japan in 2000.

Astrometry— The branch of astronomy concerned with measuring the position of astronomical objects.

AU: Astronomical unit— The mean distance from the Sun to Earth, about 150 million kilometers, often used to gauge solar system distances.

AXAF: Advanced X-Ray Astrophysics Facility— Space-based x-ray telescope with a highly elliptical orbit operating in the range of 0.1 to 10 keV. The facility is to be launched by NASA in 1998.

Axion— A hypothetical elementary particle whose existence might explain certain particle physics experiments. A candidate for dark matter.

Baryons— Heavy subatomic particles that interact strongly in nuclei. The lowest-mass examples are the proton and neutron.

BATSE: Burst and Transient Source Experiment— A gamma-ray burst monitoring instrument on NASA's Compton Gamma-Ray Observatory.

Big bang— The leading theory about the origin of the universe. It postulates that some 10 billion to 20 billion years ago the universe was in an initial state of very high density and temperature and has been expanding and cooling ever since.

Bipolar flows— Outflows, or jets, of matter from opposite poles of astronomical bodies such as protostars. The composition of, and mechanisms responsible for, such flows are not yet well understood.

Blackbody radiation— The characteristic radiation from a hot body. Its spectral properties are determined by the body's temperature.

Black hole— A region of space where the density of matter is so great, and the pull of gravity so strong, that not even light can escape. Black holes are thought to be the end point in the evolution of some stars. Massive black holes may be located at the centers of some active galaxies.

Blazar— A class of active galactic nuclei characterized by high variability in flux and polarization; a large fraction exhibits apparent superluminal motion, indicating relativistic flow.

Blue stragglers— Anomalously bright, blue stars found in certain star clusters; they may be binary stars.

Bolometric flux— A star's total energy output as measured over the entire electromagnetic spectrum.

Cataclysmic variables— Binary stars consisting of one normal star and a white dwarf, where the normal star loses matter to the white dwarf via an accretion disk. Cataclysmic variables experience repeated eruptive outbursts that increase their apparent brightness by a factor of 10 or more for short periods of time. The periods for these eruptive variables range from days to more than 10^4 years. The category includes stars such as classical novae (outbursts caused by a thermonuclear explosion on the white dwarf's surface), and dwarf novae (outbursts caused by unstable and irregular mass flow between the stars).

CCD: Charge-coupled device— An electronic detector used for low-light-level imaging and astronomical observations. CCDs have now replaced photographic emulsions for sensing visible light in most astronomical applications.

Cepheld variables— A type of supergiant star whose brightness varies in a predictable manner over a period of between 5 and 10 days. Since a Cepheid's oscillation period is directly related to its intrinsic luminosity, its distance can be calculated. Cepheid variable are one of the key yardsticks used to calculate extragalactic distances.

CGRO: Compton Gamma-Ray Observatory— Low Earth-orbiting satellite with instruments monitoring gammaray emissions in the 0.1- to 30-GeV range. CGRO was launched by NASA in 1991.

Chandrasekhar mass— The mass above which a white dwarf star would formally shrink to zero radius owing to its inability to counter its own gravity.

CMBR: Cosmic microwave background radiation— Radiation emitted approximately 100,000 years after the big bang that created the universe. As the universe expanded, the radiation cooled. It is now detectable as microwave blackbody radiation like that emitted by an object with a temperature of 2.73 K.

COBE: Cosmic Background Explorer— Low Earth-orbiting satellite designed to study the cosmic microwave background radiation using a series of infrared and microwave instruments operating in the 1.25- to 210-micron range. COBE was launched by NASA in 1989.

COBRAS/SAMBA— See *Planck*.

Cosmological constant, Λ— A hypothetical repulsive force of unknown origin introduced by Einstein in an attempt to construct a static model of the universe. Today, its value is usually assumed to be zero, but this has not been formally demonstrated.

Cyclotron emission— The characteristic radiation emitted by electrons spiraling around magnetic field lines. This emission is circularly polarized and its wavelength is inversely proportional to the strength of the magnetic field.

Dark matter— The matter in the universe that has so far escaped our detection. The presence of this unseen matter has been inferred from its gravitational influence on the motions of stars and gas in galaxies and the behavior of galaxy clusters.

Deceleration parameter, q_0— A measure of the rate at which the expansion of the universe is retarded by gravity.

Delta Scuti star— A type of main sequence variable star that oscillates in brightness with periods of several hours. Like the Cepheld variables, Delta Scuti stars are used to measure cosmic distances.

Double degenerate systems— A binary star system in which both companions are compact objects (any combination of white dwarfs, neutron stars, or black holes).

EGRET: Energetic Gamma-Ray Experiment Telescope— A gamma-ray telescope designed to study faint point-source and diffuse emissions, on NASA's Compton Gamma-Ray Observatory.

ESA: European Space Agency.

EUVE: Extreme Ultraviolet Explorer— Low Earth-orbiting ultraviolet telescope equipped with instrumentation operating in the 7- to 76-nm range. EUVE was launched by NASA in 1992.

Event horizon— The border around a black hole beyond which nothing, not even light, can escape the pull of gravity.

EXOSAT: European X-Ray Observing Satellite — Space-based x-ray telescope with a highly elliptical orbit sensitive to radiation in the 0.05-to 50-keV range. The telescope was launched by the European Space Agency in 1983.

False-vacuum energy— The difference between the current value of the energy density of empty space and its value at the beginning of the universe.

Fermi acceleration— A theoretical process by which cosmic rays may achieve their observed high energies.

Fly's Eye— An air-shower detector array located in Utah and capable of detecting cosmic rays with energies above 10^{14} keV.

FUSE: Far-Ultraviolet Spectroscopic Explorer — Low Earth-orbiting ultraviolet telescope working in the 90- to 120-nm range. FUSE, nominally the first of NASA's mid-size Explorer (Midex) missions, is to be launched in 1998.

Gamma-ray burst— A sudden, intense multipeaked burst of gamma rays with energies greater than 100 keV. These bursts typically last for a few seconds to a minute and do not appear to repeat. Their source is currently unknown, but their uniform distribution across the sky suggests that they arise in either a spherical halo about the galaxy or at cosmological distances.

GBT: Greenbank Telescope— A very large, ground-based radio telescope currently under construction at the National Radio Astronomy Observatory in Greenbank, West Virginia.

Ginga— Low Earth-orbiting x-ray telescope and gamma-ray burst detector operating in the 1- to 37-keV range in x rays and in the 1- to 400-keV range for gamma-ray bursts. This Japanese spacecraft was placed into orbit in 1987.

GMC: Giant molecular cloud— Region in interstellar space in which nearly all the matter is in the form of cold molecular gas, mainly hydrogen, but with many organic compounds as well. These clouds are the largest, most massive, and coldest known objects in our galaxy and are the current sites of star formation.

Gravitational lens— A consequence of the ability of gravity to bend the path of light rays. Astronomers have observed that the light from a distant galaxy or star can be "lensed" by the gravitational fields of intervening objects to form multiple, typically distorted images of the background object.

Gravothermal instability — A consequence of the action of the second law of thermodynamics on the intrinsic gravitational dynamics of globular clusters, resulting in a continuing flow of energy from the cluster to its environment. Heavier stars in the cluster move toward the center, releasing gravitational binding energy that imparts kinetic energy to the core stars, which then share this energy with the lighter stars through subsequent interactions. The lighter stars nearer the edge of the cluster pick up velocity, increasing their likelihood of ejection from the cluster while the heavier stars continue to contract toward the center.

Great Attractor— A supercluster-sized enhancement of dark matter and galaxies postulated to explain observed, local perturbations of the Hubbell expansion. The Great Attractor has a mass of some 10^{16} solar masses spread over 100 to 200 MPC and is located at a distance of approximately 50 Mpc from the group of galaxies in which the Milky Way is located.

Great Wall— A linear concentration of galaxies seen in large-scale redshift surveys.

Hipparcos— Space-based optical telescope dedicated to precise measurements of the positions, parallaxes, and proper motions of stars. Hipparcos was launched by the European Space Agency in 1989.

H-R diagram: Hertzsprung-Russell diagram— A graph relating stars' color(s), or equivalently temperature(s), to their luminosity. Stars at different stages in their evolution occupy specific regions of this diagram.

HST: Hubble Space Telescope— Low Earth-orbiting visible, ultraviolet, and near-infrared telescope. HST was placed into orbit by NASA in 1990.

HUT: Hopkins Ultraviolet Telescope— Shuttle-based ultraviolet telescope sensitive to radiation in the spectral range of 42 to 185 nm. HUT was flown on NASA's STS 35 (Astro-1) and STS 67 (Astro-2), in 1990 and 1995, respectively.

Hubble constant, H_0— The rate at which the universe is expanding. Actually, the Hubble constant is not really a constant at all, as it is subject to a gradual slowdown (see *deceleration parameter*).

IRAS: Infrared Astronomical Satellite— Low Earth-orbiting infrared telescope designed to survey the entire sky in the spectral range between 12 and 100 microns. IRAS, a cooperative program between NASA, the United Kingdom, and the Netherlands, was launched in 1983 and ceased operation in 1984.

ISO: Infrared Space Observatory— Space-based infrared telescope, designed as a follow-on to IRAS and sensitive to radiation in the 8- to 120-micron band. The observatory was launched into a highly elliptical orbit by the European Space Agency in 1995.

Isochrones— Lines on the Hertzsprung-Russell diagram connecting stars of constant age.

ISM: Interstellar medium— The gas and dust found between the stars.

IUE: International Ultraviolet Explorer— High Earth-orbiting ultraviolet telescope designed to study astronomical objects in the 115- to 335-nm wavelength range. IUE, a cooperative mission of NASA, the United Kingdom, and the European Space Agency, was launched in 1978 and ceased operation in 1996.

KAO: Kuiper Airborne Observatory— A 0.9-meter telescope located aboard a Lockheed C-141A aircraft and designed to study radiation in the 0.3- to 1,500-micron range from altitudes in excess of 12,000 meters. KAO was first flown in 1974 and ceased operation in 1995.

Keck (William M.) telescopes— A pair of 10-meter-aperture, optical and infrared telescopes located on the summit of Mauna Kea, Hawaii.

Keplerian frequency— Orbital frequency of an object moving under the gravitational attraction of a central point mass.

Kerr geometry— The geometry of space-time near a rotating black hole.

Kuiper Belt— A disk-shaped distribution of small icy bodies, extending hundreds of astronomical units beyond Neptune, believed to be the source of the short-period comets seen in the inner solar system.

Light curve— A plot of the variation in the brightness of an astronomical body as a function of time.

LIGO: Laser Interferometer Gravitational Wave Observatory— Interferometric gravitational-wave detector under construction at sites in Washington and Louisiana.

Lyman-Alpha line— The spectral line with a wavelength of 121.6 nm that results from a transition between the lowest two major energy levels of the hydrogen atom.

MACHOS: Massive compact halo objects— A population of objects in the halo of the Milky Way discovered via their gravitational lensing effect on the starlight from more distant stars.

Magellanic Cloud, Large and Small— The two closest galaxies to our own Milky Way. They are located about 180,000 light-years away and are visible in the southern sky. A bright supernova, SN1987A, was observed in the Large Magellanic Cloud in 1987.

Magnetic monopole— A massive elementary particle carrying a free north or south magnetic pole, postulated by some theories of elementary-particle physics but as yet unobserved.

Main sequence— The region on the Hertzsprung-Russell diagram occupied by stars burning hydrogen into helium in their cores.

MAP: Microwave Anisotropy Probe— A Midex mission designed to detect small variations in the temperature of the cosmic microwave background radiation. It is scheduled for launch in 2000.

Mass function— The relative number as a function of mass of a given class of astronomical objects.

Midex: Mid-size Explorer— A continuing line in NASA's budget dedicated to missions designed to address important questions in astrophysics and space physics. They have limited development schedules and their budgets are capped at $70 million. While FUSE is nominally the first Midex mission, it was initiated as a traditional Explorer mission and its budget exceeds the cost cap.

MMA: Millimeter Array— A National Radio Astronomy Observatory proposal to construct an interferometer consisting of 40 or more ground-based telescopes to study millimeter-wavelength radiation. Sites in Hawaii and Chile are under consideration.

Neutron star— The final evolutionary stage for larger stars, in which they have exhausted their thermonuclear fuel and radiate relic heat. Neutron stars are extremely dense and are supported by neutron degeneracy pressure.

NICMOS: Near-Infrared Camera and Multi-Object Spectrometer— Near-infrared camera installed on HST in February 1997 and designed to operate in the 0.8- to 2.5-micron band.

Nova— An extreme example of the cataclysmic variable phenomenon in which a star's brightness suddenly increases by a factor of a million and then fades over a period of weeks. Novae occur in binary systems of one normal and one white dwarf star, where the normal star transfers matter to the dwarf via an accretion disk. The accreted matter accumulates until such time that it spontaneously ignites in a thermonuclear outburst on the white dwarf's surface.

O-B association— A group of O and B stars close together in space that are young, massive, and ultravioletluminous. The members of an O and B association were formed roughly at the same time.

OSS: Office of Space Science (NASA).

Pair plasmas— A plasma consisting of electrons and positrons.

Parallax— The apparent shift in position of a nearby object, relative to more distant ones, as the observer changes position. Using basic trigonometry, it is possible to derive the distance of a star as observed from opposite points on Earth's orbit.

pc: Parsec— A distance equal to 3.3 light-years.

Pierre Auger Array— Cosmic ray air-shower detector approved to be built, consisting of two sites, one in the United States and the other in Argentina.

Planck: Cosmic background radiation measuring mission (formerly COBRAS-SAMBA) currently under study by the European Space Agency. Its objective is to extend COBE's discovery of anisotropy in the cosmic microwave background radiation with higher resolution and greater sensitivity.

Positronium— A short-lived analog of a hydrogen atom in which the central proton is replaced by a positron.

Principle of equivalence— A basic postulate of general relativity stating that it is impossible to distinguish locally between a gravitational field and an accelerating reference frame.

Pulsars— Highly magnetic neutron stars spinning at a rapid rate and emitting regular bursts of radiation from their poles. Pulsars have been observed to emit at radio, visible, x-ray, and gamma-ray wavelengths.

QSO: quasi-stellar object— see *quasar*.

Quark stars— A hypothetical end point of stellar evolution related to a neutron star.

Quasar— An extremely distant and luminous active galactic nucleus that may outshine its parent galaxy by a factor of 1,000 or more. Sometimes called a quasi-stellar object (QSO).

q_0— see *deceleration parameter*.

Redshift, z— The shift in frequency (making objects appear redder than they actually are) of radiation emitted from a body that is receding from the observer. The expansion of the universe makes objects recede from us, causing the light we see from distant galaxies to be redshifted; the higher the redshift, the farther away the object. Redshift is often denoted by *z*, where $z = v/c$ and c is the velocity of light and v the velocity of the object. The wavelength shift is then given by the factor $(1 + z)$.

Relic elementary particles— Elementary particles left over from the first moments after the big bang.

ROSAT: Roentgensatellit— Low Earth-orbiting x-ray telescope functioning in the 0. l- to 2.0-keV range. ROSAT, a cooperative mission between Germany, NASA, and the United Kingdom, was launched in 1990.

r-process— The process by which elements are formed when an atomic nucleus captures neutrons on a time scale that is very short compared to the time required for the nuclei to decay via the emission of a beta particle. This mechanism, believed to operate in supernovae, is responsible for the creation of many of the elements in the periodic table more massive than iron. See also, *s-process*.

RR Lyrae star— A type of star that oscillates in brightness with a period of approximately 12 hours. Such stars are sometimes called short-period cluster variables. All RR Lyrae stars have approximately equal intrinsic luminosities and so are used to determine the distances to globular clusters.

RXTE: Rossi X-Ray Timing Explorer— Low Earth-orbiting x-ray telescope working in the 2- to 250-keV range. The telescope was launched by NASA in 1995.

SAX: Satellite per Astronomia in Raggi X— An Italian-Dutch x-ray satellite designed to operate in the 0. l- to 200-keV waveband. This spacecraft, also known as BeppoSAX, was launched in April 1996.

Schwarzschild geometry— The geometry of space-time near a non-rotating black role.

Soft gamma-ray repeaters— Extremely short-duration (typically less than 1 second) bursts of relatively low-energy gamma rays. Unlike the classical gamma-ray bursts, soft gamma-ray repeaters undergo repeated bursts. Recent observations suggest that they are associated with supernova remnants in our galaxy.

SIRTF: Space Infrared Telescope Facility— Low Earth-orbiting infrared telescope, the last of NASA's Great Observatories, functioning in the range of 4 to 180 microns. The facility is scheduled for launch in 2001.

Sloan Digital Sky Survey— Five-year program to measure the positions and redshifts of some 10^6 galaxies using a dedicated telescope located at Apache Point Observatory in New Mexico.

SOFIA: Stratospheric Observatory for Infrared Astronomy— A Boeing 747 aircraft equipped with a 2.5-meter telescope, designed to study infrared and submillimeter emissions in the 0.3- to 1,600-micron band. The first flight of this NASA-German cooperative project is scheduled for 2000.

Spallation— The shattering of a nucleus by a highly energetic cosmic ray particle.

Spiral density waves— The mechanism by which the arms of spiral galaxies are formed and maintained by a periodic perturbation in a galaxy's gravitational field.

s-process— The mechanism by which elements are formed when atomic nuclei capture neutrons on time scales that are very long compared to the time required for the nuclei to decay via the emission of a beta particle. In contrast to the r-process operating in supernovae, the s-process occurs in normal stars. This process is responsible for the creation of many of the elements heavier than iron that are not created by the r-process.

Starburst galaxies— Bright sources of infrared radiation created when a galaxy forms stars at a rate hundreds of times greater than that observed in the Milky Way. These bursts of star formation may be triggered when a galaxy is perturbed by a close encounter or collision with another galaxy.

Stark broadening— The broadening of spectral lines due to the electric fields of nearby charged particles. The degree of broadening increases with pressure and is therefore a measure of high gravity.

Stellar dynamo— The as yet unknown internal process or processes by which a star's magnetic field is generated.

STIS: Space Telescope Imaging Spectrograph— A two-dimensional spectrograph operating at ultraviolet, optical, and near-infrared wavelengths. The instrument was installed in HST in February 1997.

Sunyaev-Zeldovich effect— A temperature dip in the cosmic microwave background radiation associate with hot, x-ray-emitting gas in clusters of galaxies.

Supernova— A star that, due to accretion of matter from a companion star (Type Ia) or exhaustion of its own fuel supply (Types Ib, Ic, and II), can no longer support itself against gravity and thus collapses, throwing off its outer layers in a burst of energy that may briefly outshine an entire galaxy.

T Tauri star— A type of irregularly varying star whose spectrum shows broad and very intense emission lines. T Tauri stars are believed to be very young and have not yet settled onto the main sequence depicted in the Hertzsprung-Russell diagram.

Two-Degree Field Survey— A project designed to measure the redshifts of a large number of galaxies in the Southern Hemisphere. It will be performed with the 3.9-meter Anglo-Australian Telescope using a flexible fiber-optic system capable of simultaneously measuring the spectra of up to 400 objects over a two-degree field of view.

2MASS: 2-Micron All-Sky Survey— All-sky infrared survey using telescopes located on Mt. Hopkins, Arizona, and Cerro Tololo, Chile.

Type Ia supernova— A supernova occurring in a binary system that contains a white dwarf which is accreting mass from a companion star. Their spectra show a strong silicon line but no evidence of hydrogen or helium. All Type Ia supernova are believed to have the same brightness, allowing them to be used as beacons to measure extragalactic distances. Type Ibi supernovae show strong helium lines; Type Ic display no hydrogen, helium, or silicon lines. Both of these types occur in the arms of spiral galaxies and are assumed to result from the core collapse of massive stars that would have ended their lives as Type II supernovae except that they have lost their hydrogen (and helium, for Type Ic) envelopes to some combination of winds and mass transfer.

VIRGO— A laser gravitational wave interferometer under construction near Pisa in Italy.

VLA: Very Large Array— Ground-based radio interferometer, located in New Mexico and operated by the National Radio Astronomy Observatory, consisting of 27 telescopes arranged in a Y-shaped array with arms 21 km long.

VLBA: Very Long Baseline Array— A network of radio telescopes with elements located in Hawaii, the continental United States, and the U.S. Virgin Islands. The array, operated by the National Radio Astronomy Observatory, is dedicated to VLBI observations.

VLBI: Very Long Baseline Interferometry— The simultaneous observation of a single object with an array of radio telescopes that are separated by very large distances, even across or between continents. The signals received at each telescope can be combined to synthesize what would have been seen by a single telescope as large as the array.

VSOP: VLBI Space Observatory Program— An 8-meter-diameter radio telescope placed in a highly elliptical orbit about Earth in February 1997 as a part of an Earth-space VLBI network. This Japanese project is also known as the Highly Advanced Laboratory for Communication and Astronomy (HALCA).

White dwarf— The final evolutionary stage for an average star (around 0.7 to 1.4 solar masses), when it has exhausted all of its nuclear fuel and is radiating away its internal heat. White dwarfs are highly dense and are supported against gravity by the pressure of degenerate electrons.

Wolf-Rayet star— A type of very hot star whose spectrum shows very broad emission lines of helium and hydrogen.

XMM: X-Ray Multi-Mirror— Space-based x-ray telescope with a highly elliptical orbit, dedicated to spectroscopic observations in the 0.1- to 5-nm range. This European Space Agency satellite is to be launched in 1999.

z— See *redshift*.