SETTING PRIORITIES *for* SPACE RESEARCH

Opportunities *and* Imperatives

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Setting Priorities for Space Research

Opportunities and Imperatives

Task Group on Priorities in Space Research—Phase One

Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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TASK GROUP ON PRIORITIES IN SPACE RESEARCH—PHASE ONE

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Preface

This report represents the first phase of a study by a task group convened by the Space Studies Board to ascertain whether it should attempt to develop a methodology for recommending priorities among the various initiatives in space research (that is, scientific activities concerned with phenomena in space or utilizing observations from space). The report argues that such priority statements by the space research community are both necessary and desirable and would contribute to the formulation and implementation of public policy.

The report advocates the establishment of priorities to enhance effective management of the nation's scientific research program in space. It argues that scientific objectives and purposes should determine how and under what circumstances scientific research should be done. The report does not take a position on the controversy between advocates of manned space exploration and those who favor the exclusive use of unmanned space vehicles. Nor does the report address questions about the value or appropriateness of Space Station Freedom or proposals to establish a permanent manned Moon base or to undertake a manned mission to Mars.[1] These issues lie beyond the charge to the task group.

[1]For further discussions in National Research Council reports on the role of manned versus unmanned spaceflight, see *Human Exploration of Space—A Review of NASA's 90-Day Study Alternatives* (1990), *Toward a New Era in Space—Realigning Policies to New Realities* (1988), *Report of the Committee on the Space Station of the National Research Council* (1987), *A Strategy for Space Biology and Medical Sciences for the 1980's and 1990's* (1987), and *Space Science in the Twenty-First Century—Imperatives for the Decades 1995 to 2015—Overview* (1988) (National Academy Press, Washington, D.C.); and "The Nation's Space Program After *Challenger*: The Need for a Reassessment of the Roles of Manned and Unmanned Systems for Launching Scientific Space Missions" (1986), an unpublished report of the Space Studies Board.

We believe that the vision, objectives, and operating principles we propose are compatible with the objectives of the human spaceflight program and could contribute to a vigorous space program at all levels. For this reason, we commend these proposals to those responsible for the entire space program for their consideration. In general, the efforts of the space research community have concentrated on setting priorities for scientific research and assessing the scientific merit of proposed space research missions. One issue considered here is whether the space research community should take a more active role in recommending a hierarchy of priorities to guide the program. A second issue is what considerations should influence priorities and the criteria used to determine them.

The Space Studies Board is interested in priorities for several reasons. First, as a result of a reexamination and redefinition of its role in 1988 and 1989, the Board expanded its advisory perspective and initiated studies of broad issues associated with management of the civil space program. Second, the numerous opportunities for space research initiatives far exceed available resources; thus choices among them must be made. Finally, there is evidence that both Congress and some members of the scientific community are interested in developing a reasoned approach to creating a national scientific research agenda with explicit priorities assigned to various categories of effort.[2]

This report is intended for an audience that includes the scientific community and policymakers in the executive branch and Congress. The Board is mindful of the prospect that its efforts may lead to a model that could be useful in a broader context of determining priorities for a national scientific research agenda.

This first phase of the Space Studies Board's examination of priorities in space research began with a workshop in the summer of 1989 that considered the broad spectrum of research and development activities in the United States and the complex decision-making process governing them. Participants represented diverse backgrounds, including science, finance, economics, industry, and flight programs, and included representatives of Congress, the Office of Management and Budget, and NASA.

[2]For examples of recent congressional views on finite resources and accompanying difficult choices, see the House and Senate reports on H.R. 2519 (Reports 102-94 and 102-000, respectively; U.S. Government Printing Office, Washington, D.C.), which provides 1992 appropriations for the Department of Veterans Affairs, the Department of Housing and Urban Development, and independent agencies. For an example of the scientific community's interest in this issue, see Space and Earth Sciences Advisory Committee, *The Crisis in Space and Earth Sciences—A Time for a New Commitment* (NASA Advisory Council, 1986) or "The Dilemma of the Golden Age," address by National Academy of Sciences (NAS) President Frank Press to NAS members (April 1988).

Extending the discussions of the workshop, this report considers the rapidly changing context in which federal research activities occur and argues for a rationale for recommending priorities in space research that is consistent with national goals. To set the stage, the report documents the accomplishments of the national space research program and surveys the exciting opportunities ahead. The next phase of the study will attempt to develop a credible methodology that the Board and the space research community could use to recommend priorities and will be published separately upon its completion.

Such a set of priorities must be created in a context broader than that of space research alone.[3] In the more than 30 years since the national space program began, there have been vast changes in the United States and in the world. The complexity of the federal decision-making process has increased in proportion to the ever-increasing array of federal activities. There are continually evolving internal and external pressures at each and every level of the process. Choices and deliberations within the federal agencies, the presidential offices, and Congress are shaped by national goals, global economic competition, the consequences of the federal budget deficit, domestic politics, national security concerns, and the powerful but often unpredictable forces of public opinion.

These realities must be addressed in the process of considering priorities for space research. Some will insist that space researchers should not attempt to provide advice about the implications of issues other than the scientific merit of proposed space missions. This report argues that scientific research in space, and (by implication) the entire civil space research program, will better serve the goals of both science and the nation if the priorities that govern them simultaneously reflect both scientific and broader national imperatives. Helping to fashion the appropriate criteria thus becomes a responsibility of the space research community. The community is capable of making the sophisticated judgments necessary to foster a vital and robust space research program: We believe it must do so.

[3]For further discussions on the issue of priority setting, see also Office of Technology Assessment, *Federally Funded Research: Decisions for a Decade* (U.S. Government Printing Office, Washington, D.C., 1991).

Contents

[Policy] is like a play in many acts, which unfolds inevitably once the curtain is raised. To declare that the performance will not take place is an absurdity. The play will go on, either by means of the actors . . . or by means of the spectators who mount the stage.

Klemens von Metternich

Summary and Recommendations

The U.S. space program and its space research components have produced remarkable achievements in the past three decades and generated a wealth of opportunities for scientific initiatives in the years ahead. As we approach a new century, we must decide: What should we do? How should we do it?

Answers to these questions are critical for the future success of the space program and space research (that is, scientific activities concerned with phenomena in space or utilizing observations made in, or from, space). The answers will affect the strength of the national scientific and engineering enterprise, national economic vitality, and the national sense of pride and purpose. Answering the first question is equivalent to setting priorities for space research. Answering the second question requires that we develop a model for our activities that will facilitate accomplishing our highest-priority activities. Priorities, as used here, are rankings in a preferential ordering or agenda, possibly multidimensional, that governs allocation of resources to activities or initiatives.

For some time, the objectives of the space research community and those of the broader space program have been in conflict. Apollo demonstrated national technological superiority at a critical time. A fundamental assumption of the civil space program developed in that era asserts that it is human destiny to explore the universe. As a consequence, the civil space program continues to emphasize the mechanical aspects of flying spacecraft and transporting humans through space. In contrast, scientific vision focuses on the outcome of space activities, insisting that the means of conducting scientific research be determined by the objectives and purposes of that research itself; it emphasizes the information and understanding generated rather than the means of obtaining them.

New realities of international competition, domestic politics, and economics suggest the need to review the contributions of space research to national vitality. The accomplishments of the past and the many opportunities now available, as well as the widely recognized need to provide stimulation and motivation to education, suggest that we reconsider how scientific research in space is conducted. Fundamental assumptions about the objectives of space research and the space program that makes it possible may determine the outcome of research more than judgments about scientific merit, or national values, or imperatives presented by the new realities mentioned above. Thus the issue is not the relative value of the human spaceflight and space research components of the space program. Rather, it is to develop objectives and operating principles that will produce the maximum benefits from the nation's investment in space research and other space activities.

The imperative driving scientific research is the acquisition of knowledge and understanding. The collection of data, the creation of information through its analysis, and the subsequent development of insight and understanding should be key governing objectives for scientific research in space and for the broader program. As suggested in the preface, the task group believes that this vision is compatible with the human spaceflight program and that the entire space program itself would be invigorated by concentrating on timely and compelling scientific objectives.

Emphasizing information and understanding will not compromise the overall space program's legitimate interest in the technology of spaceflight, because formidable engineering and technical challenges must be met in order for space research to achieve its objectives. It will, however, permit the space research program and the overall space program to concentrate on the development of powerful new techniques for acquiring, communicating, synthesizing, and using information. And because information itself is an increasingly critical and economically valuable resource, this effort can enhance our national technological progress and economic strength while it enhances our scientific accomplishments.

Thus the vision of a space program and a space research effort emphasizing information, knowledge, and understanding presents an ideal format in which to consider priorities for space research. The central thesis of this report is that the space science and applications community should reach a consensus on priorities for scientific research in space. Since we cannot do everything, we should do the most valuable things, with the recognition that a collection of smaller efforts may in sum be more important than a single large initiative. The task group believes that a scientific agenda set forth by the community, with due regard for contemporary political and economic realities, will greatly assist policymakers and will ultimately prevail. Such an agenda, along with the reformulation of assumptions governing space research, will better serve scientific and national goals, achieve maximum return on investment, encourage effective congressional and agency action, and provide benefits for the nation's citizens.

ACCOMPLISHMENTS, PROSPECTS, AND LESSONS FROM THE U.S. SPACE RESEARCH PROGRAM

The accomplishments since 1957 of U.S. scientific research in space have broadened and deepened understanding of our physical environment. As with all science, these accomplishments are but harbingers of even greater future achievements. Past successes have created a multiplicity of opportunities for space science and applications. Moreover, our more than 30 years of experience in space research have provided important lessons on how to operate the program more effectively in order to obtain the maximum possible benefit from available resources.

All disciplines reveal the complexity of the physical and biological world. Things are much more complicated than we thought at the beginning of the space age in 1957. As examples, consider the violent astronomical events, the courses of planetary evolution, the interactions of solar and terrestrial magnetic processes, the interdependence of the various components of the Earth system, and the changes in human physiology that occur in space. We can expect to discover even more variety and more complexity in the years ahead.

Perhaps the most striking accomplishment of the U.S. space program is the demonstration that humans can work in space and on another body of the solar system and can travel to another part of the solar system and return successfully. This demonstration has opened the way for human exploration beyond the Earth for centuries to come.

The value of the unique point of view attainable from space has been demonstrated beyond doubt. We gain more than just a different perspective: operating far from the Earth's surface expands the domain of parameters available to science. This expansion will continue with the return and analysis of samples from planets, asteroids, and comets, with observations that reach back even further toward the origins of the universe, with extended human presence in space, and with comprehensive views of the interactions of the Earth's physical and biological subsystems.

In over 30 years of experience in space research, we have learned that flexibility and multiplicity of opportunity are key requirements. Although large missions may address the most urgent or most comprehensive scientific issues, small or moderate missions and suborbital initiatives can also resolve important scientific questions, and can do so more quickly and less expensively. For space research to produce maximum benefits, the objectives of scientific research should drive the mission rather than constraints imposed by the limitations of a program or a particular launch vehicle.

TODAY'S IMPERATIVES

Recent events at home and abroad require that we reexamine motivations, objectives, and methods of space research to ensure that they are responsive to contemporary imperatives. The key imperatives and their implications are as follows:

- Rapidly changing relationships between nations create new challenges and opportunities. Scientific efforts and space research must contribute to our ability to succeed in a vigorous economic and technological international competition.
- Domestic needs compete with scientific research in space and with the space program and force the nation to choose between research opportunities and other endeavors. Thus a focused and compelling space research agenda that clarifies the value and increases the productivity of both space research and the space program must be formulated.
- Public demand for accountability and for effective use of available resources is increasing. Space research and the space program must be conducted in accord with operating principles that will ensure that objectives are attained effectively. We must distinguish between initiatives in space that contribute to scientific understanding and those that are really aimed at nonscientific public purposes.
- There is widespread concern that our educational systems are not adequately preparing our citizens to participate effectively in an increasingly technological and competitive world. Success in space research can stimulate the curiosity of all young Americans and motivate some to choose careers in science, engineering, and technology disciplines. A vigorous space science program will provide information that interests, and perhaps enlightens, a national audience.
- Opportunities for international collaboration in space research are increasing. They are attractive because of the increasing complexity and cost of acquiring knowledge. But sharing the costs of space research with others cannot alone justify international collaboration; rather collaboration should be undertaken in space research only to enhance scientific achievement.

OPERATING PRINCIPLES

Space research and the space program must be managed according to operating principles that will ensure that resources are used effectively and that objectives are attained. The following principles are derived from our 30 years of experience in space research; adhering to them will enhance the acquisition of information and knowledge and facilitate the response of space research and the space program to today's imperatives.

• **Enhance the human resource base.** The community of working scientists and students should be maintained and invigorated to strengthen the national scientific enterprise.

• **Acknowledge that choices must be made.** Science raises more intriguing questions than can be answered or even addressed. Thus we should recognize that choices must be made.

• **Capitalize on opportunities.** Special opportunities to perform good research are sometimes offered by technological developments or demands for applications. Wise investments in technological development will create such opportunities, sometimes in unexpected ways.

• **Capitalize on investments.** Having chosen to start valuable projects, we should insist on finishing them, in satisfactory, cost-effective ways. We need to understand better the direct and indirect costs of abandoning projects already begun.

• **Increase program control by principals.** Making principal investigators responsible for quality and giving scientists an increased role in program management offer potentially large benefits.

• **Secure access to space by diverse means.** Access to space through a variety of means appropriate to particular research missions is a recognized requirement of a vital space program.

THE RATIONALE FOR SETTING PRIORITIES

Priorities are needed at several levels within the national scientific enterprise, within the space program, and within space research because the success of science has created a wealth of opportunities for initiatives. Some initiatives will contribute more to scientific knowledge than others, some will enhance national economic and technological vitality, some will advance important applications of information from space, and some will assist in resolving important policy issues. An orderly process is needed to make the necessary choices.

Chapter 2 illustrates the broad range of future prospects for space research that includes large and small missions, projects in different fields, and the need to support both mature fields and untested ideas. Developing priorities for scientific research in space requires a sophisticated approach because it is not possible to rank all scientific research activities in a single list. Any priority scheme should be multidimensional in nature, with certain classes of activities given higher priority than others. There are a number of important criteria: the value of an initiative to science, potential social benefits, costs and readiness to perform it, and the probability of success. A priority scheme should provide for balance and flexibility in the program and for the maintenance of essential, ongoing activities.

Arguments for Setting Priorities

There are two principal arguments in favor of the recommendation of an agenda for space research by the scientific community:

- **Consensus is politically compelling.** An agenda for scientific research in space created and supported by the community would be persuasive. If scientists demonstrate that their agenda responds to scientific imperatives and to national needs, they can argue effectively for an adequate share of resources and for an orderly progression through the suite of initiatives endorsed by the community.
- **If scientists will not act, then others will.** If scientists cannot, or will not, recommend priorities, then others whose goals may differ from those of the scientific community will take the stage and make the decisions. None of the reasons scientists cite for eschewing the strenuous work of reaching consensus prevents federal officials or congressional representatives from making the necessary choices.

Addressing the Arguments Against Setting Priorities

A number of arguments against recommending priorities are sometimes offered by scientists. Some of them are listed below, with explanations as to why the task group does not find them compelling:

- **There will be losers.** Indeed there will be, but there are losers now. In fact, some who now enter the priority-setting process lose for reasons unrelated to the quality of the science. It would seem preferable that the community of scientists help to determine the winners.
- **Recommending priorities is too difficult, too contentious.** Recommending priorities is difficult but can be accomplished through a formal process in which competing initiatives are judged uniformly according to

explicit criteria. If scientists find it too difficult to create a recommended program for space research, then, as said above, others will do it for them.

• **The community will not be able to maintain consensus.** Scientists loyal to initiatives not receiving strong recommendations may tend to subvert the process, it is argued, by lobbying for special favor. They would be better advised to develop more exciting initiatives. This argument and the two above combine to make a fourth:

• **Setting priorities will be counterproductive because the community will tear itself apart.** Moreover, the argument goes, at present the losers' rancor is directed at officials outside the community; if the community sets priorities, then the rancor will be turned inward. In essence, this is an argument that the scientific community is too immature to govern itself. The task group believes the scientific community can behave responsibly and that its best interests will be served by doing so.

• **The low-priority initiatives will not be done.** The argument is that policymakers will take advantage of any list of priorities by eliminating the low-priority activities. That is precisely the reason priorities are recommended. It certainly seems preferable to abandon low-priority activities rather than to starve those with high priority.

• **Scientists cannot make political judgments.** Once scientifically meritorious proposals are put forward, this argument goes, the judgments about relative social benefits and the relevance to national needs are beyond the purview of scientists. But the task group believes that in arguing for initiatives, scientists should be sensitive to national goals and political realities. Because scientists expect support from the public, they should be able to explain why some initiatives better serve public purposes.

Priorities have been successfully set by scientists in a number of contexts. For example, NASA's Office of Space Science and Applications (OSSA) has adopted a structured approach to the assignment of priorities using the priority recommendations of a scientific advisory committee. The result is a program in which annual budget requests are made in the context of a formal five-year plan. Clarifying the components of the program and specifically setting priorities among initiatives appear to have reduced uncertainty and divisiveness in the space research community, strengthened space research, and made the program more attractive to the policymakers who provide the resources for it.

CONCLUSION AND RECOMMENDATIONS

Space research operates within the vision that governs the overall civilian space program. The task group concludes that emphasizing the acquisition and processing of observations and information and the conversion of this information into knowledge and understanding will simultaneously advance science and contribute effectively to national economic and technological vitality. Even with such a vision, the need to determine priorities among the various initiatives is inevitable.

For these reasons the task group makes the following recommendations:

- Development of new knowledge and enhanced understanding of the physical world and our interactions with it should be emphasized as the principal objective of space research and as a key motivation for the space program.
- Acquisition and effective management of information derived from space should be a primary objective of our national activities in space. Concentrating on innovation in information management will produce benefits beyond space research.
- The requirements of space research itself should determine policy and programmatic decisions in space research and in the support of space research by the civil space program.

Finally, the task group recommends that the Space Studies Board proceed to the next phase of the Priorities in Space Research Study and thereby develop a methodology for assessing priorities for scientific research in space. Such an assessment procedure is possible, and its application will allow the establishment of priorities in space research that will benefit science, the U.S. civil space program, and the nation. The members of the scientific community conducting research in space have a responsibility to the public to undertake this task.

1

Setting the Course for Space Research

In response to national goals set more than three decades ago, the U.S. space program and its space research components have produced remarkable scientific and technological achievements. Apollo propelled the United States into a position of world technological leadership. Scientific missions have surveyed the heavens and the Earth itself, sending back information that has given us deeper understanding of the nature of our physical world and the universe around us. Success in space science and applications has generated even greater opportunities for future accomplishment. Now, for the years ahead, we must decide what we should do and how we should do it.

The fundamental assumption shaping the U.S. civil space program, and consequently space research, was expressed in the Apollo era "as the manifestation of a vision—the vision that our human destiny is to explore the universe."[1] In this context, the military metaphor of "mission" has been used to refer to all space activities, including scientific research. The use of this term emphasizes the penetration of a difficult domain, rather than the information and knowledge to be acquired. The Apollo perspective continues to guide the program; the Space Station is intended to provide "a permanent manned presence" in space, and the President has set the "long-range goal of expanding human presence and activity beyond Earth orbit into the Solar system."[2]

Unfortunately, the goals and accomplishments of the scientific community have sometimes been constrained by the Apollo vision. Scientific efforts focus on the outcome of an activity (e.g., an experiment, observation, simulation, or derivation) by concentrating on the knowledge or understanding to be gained. The successful flight of a spacecraft conveying scientific experiments is a means to that end.

The space program serves a variety of important national goals, including fostering national pride and prestige, developing and maintaining economic and technological vitality, and generating scientific information and understanding. The issue addressed here is not the relative value of the human spaceflight or space research components of the program. Rather, this report seeks to contribute to the development of a vision along with objectives and operating principles that will assist the nation in realizing the maximum benefits from its investment in space research and other space activities. The value of any initiative or activity in the space program is measured by the extent to which it serves national goals. Initiatives that advance all of these goals should be preferable to those with more limited contributions. From the national perspective, a scientific mission that is technologically challenging may be preferable to one that employs routine capabilities. In turn, a crewed mission or a facility with a governing scientific purpose will be more valuable than one that demonstrates technological capability alone. Thus scientific research may be served by both crewed and robotic missions that concentrate on the timely acquisition of information and scientific and technical knowledge, and these objectives are compatible with all aspects of the civil space program. Furthermore, these objectives should determine how access to space is achieved and how scientific research in space is ultimately conducted.

This report examines some of the issues involved in setting priorities within the scientific research in space program and, to the degree that it is relevant, within the entire space program. Priorities, in the sense used here, are rankings in a preferential ordering or agenda, possibly multidimensional, that governs allocation of resources to activities or initiatives. A system of priorities appropriate for scientific research in space or for the entire space program would be more sophisticated than a simple rank ordering.

Priorities are intimately related to basic assumptions about purpose and motivation. For the space program and for space research, such assumptions may determine events more powerfully than judgments based on scientific merit or national values or shaped by the imperatives of changing economic and political conditions. For example, an emphasis on transport to space led to the launching of several scientific research vehicles (e.g., Galileo, Magellan, Ulysses, and Hubble) by the Space Shuttle regardless of whether the Shuttle was appropriate to the scientific task. The contemplation of priorities that might produce an effective agenda for space research, or for the entire space program, must include examination of fundamental assumptions and the opportunities and constraints consequent upon them.

DEFINITIONS

The U.S. space program—the totality of the national efforts in space research, applications, and engineering and technology for activities in space.

The civil space program—the civilian (nondefense) components of the space program.

The human spaceflight program—those components of the space program that involve the flight of humans in space vehicles.

Space research—Scientific activities concerned with phenomena in space, or utilizing observations obtained in, or from, space, including the use of information derived from space to advance other activities. Research in space involves observation, development of scientific instruments and scientific support technology, data management and analysis, creation of theories and models concerning phenomena observed from space, and application of space observations to further economic or socially beneficial activities.

Space science and applications—Here, synonymous with space research.

The task group's studies of priorities in space research have led it to believe that the nation would benefit if space research and much of the space program emphasized the acquisition of information and knowledge and the development of insight and understanding. Adopting the acquisition of information that cannot be obtained on Earth as the primary purpose of space activities is compatible with national needs to develop advanced technologies and capabilities. Most significantly, such a purpose provides clear objectives for future development of the human spaceflight program.

As illustrated in Chapter 2, observations from space reveal an unexpected and wondrous complexity. The objects and phenomena we have studied have turned out to be much more complex than imagined. The goal of research is to unravel this complexity, to understand its implications and to discover principles or points of view that will render it comprehensible. To do so will require an abundant flow of information from space and the capability to use it effectively. Observational and informational systems must be created to interact effectively: "The satellite and the computer are a natural partnership; one provides data, the other makes sense of it."[3] Thus an effective model for scientific research in space will emphasize the acquisition, management, and use of information from space to enhance human knowledge and understanding. It will enable us to focus on this critical commodity of the contemporary world.

The acceptance of this governing objective for scientific research in space will assist in establishing priorities. It is evident that such priorities are necessary because current opportunities for scientific research in space demand far more resources than are likely to be available in even the most optimistic scenario.

Table 1.1 summarizes the entire spectrum of NASA space science missions now active or expected by NASA planners to be launched before the year 2000. Figure 1.1 shows that the expected increase in funding required to complete present missions and to implement and launch the missions already approved for new starts exceeds an annual growth rate of 15 percent. Future new starts will require an even greater rate of increase in the budget for space research.

The increased funds required to maintain or expand the program may not be available. In commenting on the NASA budget for fiscal year 1991, the Appropriations Conference Committee of the 101st Congress observed:[4]

> It is essential that the agency recognize that the budget crisis is only beginning. The five-year budget agreement assumes an annual growth rate in domestic discretionary spending . . . of approximately five to seven percent. That fact suggests that the *maximum* annual growth in NASA's budget cannot exceed eight to ten percent.

TABLE 1.1 NASA Scientific Missions—1990 to 2000

Field	Active as of December 1990	Planned for 1991 to 2000	Total
Space physics	6	17	23
Planetary and lunar science	8	4	12
Earth sciences	2	24	26
Astrophysics	6	9	15
Life sciences	0	4	4
TOTAL	22	58	80

SOURCE: General Accounting Office. 1989. *Space Operations: Listing of NASA Scientific Missions, 1980-2000*, GAO/IMTEC-89-46FS (U.S. Government Printing Office, Washington, D.C.) April.

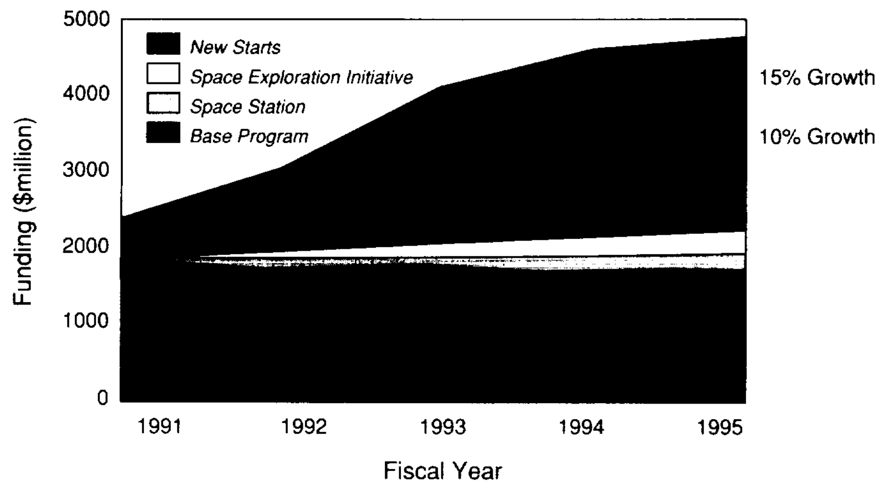

FIGURE 1.1 Funding (in $million) required to maintain the space research program, including missions now in flight and new starts already approved. SOURCE: Office of Space Science and Applications, NASA.

Thus it appears clear that NASA and the nation will have to choose among scientific research initiatives and other components of the space program. In recognition of these realities, the Advisory Committee on the Future of the U.S. Space Program recommended that science activity be "the fulcrum of the entire civil space effort." As justification, the committee argued that[5]

> . . . the space science program warrants the highest priority for funding. It, in our judgment, ranks above space stations, aerospace planes, manned missions to the planets, and many other major pursuits which often receive greater visibility. It is this endeavor in science that enables basic discovery and understanding, that uncovers the fundamental knowledge of our own planet to improve the quality of life for all people on earth, and that stimulates the education of the scientists needed for the future. Science gives vision, imagination, and direction to the space program and as such should be vigorously protected and permitted to grow, holding at or somewhat above its present fraction of NASA's budget even as the overall space budget grows.

If this recommendation is followed and there is a stronger focus on space research, then the necessity for making difficult choices will be even more urgent. There are many opportunities in space research, and thus we need a procedure by which to select those that are most valuable. The community of scientists engaged in scientific research in space should reach a consensus on priorities and thereby contribute to the formulation of an agenda for space research and for the space program. Such an agenda and the priorities it represents will need to respond to national needs and to the larger priorities of the national agenda.

The two key questions in space research, as in most continuing endeavors, are: What should we do? How should we do it? As argued above, the priorities that determine what we choose to do reflect our values. The methods we then adopt, and often our successes, are also determined by the vision and purpose that guide our activities. Careful consideration and formulation of assumptions and priorities for the scientific research program and the overall space program that supports it will enable us to better serve national goals, compel effective action, achieve the maximum return on our national investment, and inspire our citizenry.

NOTES

1. Byerly, Radford, Jr. 1989. "Introduction," in *Space Policy Reconsidered*, R. Byerly, Jr., ed. (Westview Press, Boulder, Colo.) p. 3.
2. The White House, *National Space Policy*, November 2, 1989.
3. "What's a Heaven For?," *The Economist* 319 (June 15, 1991): 3.
4. Appropriations Conference Committee of the 101st Congress. 1990. Conference Report 101-900 to Accompany H.R. 5158, "Making Appropriations for the Departments of Veterans Affairs, Housing and Urban Development, and Independent Agencies for FY 1991" (U.S. Government Printing Office, Washington, D.C.) p. 41.
5. Advisory Committee on the Future of the U.S. Space Program. 1990. *Summary and Principal Recommendations on the Future of the U.S. Space Program* (Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.).

2

The U.S. Space Research Program: Accomplishments, Prospects, Lessons

Space research concentrates on observations or experiments that are effective means of obtaining essential information, including studies of the Earth and its environment, solar and space physics, solar system characteristics, astronomy, life sciences, and fundamental physics. Each of these fields is in a different state of maturity: astronomy, earth sciences, planetary sciences, and space physics reach back to the very origins of the space program, whereas life sciences and microgravity sciences are just now emerging as longer missions offer increased opportunities for research.

The following pages summarize briefly the accomplishments and status of U.S. space research. The summary is not meant to be exhaustive but rather to provide a glimpse of what has been achieved in our space program, some ideas of opportunities that remain, and a constructive evaluation of what we have learned about program management.

SELECTED DISCOVERIES AND ACCOMPLISHMENTS OF THE U.S. SPACE RESEARCH PROGRAM

In only 30 years, space research has brought forth a rich array of expanded knowledge and understanding in all areas of space science and applications. Major discoveries have been made as we moved outside the Earth's atmosphere, found a new view of our home planet, and left behind such features of our environment as the physiological effect of gravity.

From our new vantage point, we have achieved significant understanding of many fundamental processes in the cosmos, solar system, Earth, and even our own bodies. Our constant search for origins has been aided by space observations providing new insights into the formation of the universe, the Earth, other planets, and life as we know it. Through new eyes, we see an unexpected complexity in structure and processes over a vast range of spatial scales. Closer to home, we have gained a deeper appreciation for the intricate interactions between humans and the Earth. In some areas, we have gained substantial practical applications of new knowledge and techniques.

Scientific research in space has provided answers to many questions and stimulated even more. We have learned much about larger issues such as

- **What is in our worlds?**
- **How do our worlds work?**
- **How did our worlds come to be?**
- **How do our worlds evolve?**
- **How do we affect and how are we affected by our worlds?**

These questions are used as organizing themes in the following brief review of the major accomplishments of the space sciences over the past 30 years.

Discovery—What Is in Our Worlds?

We discover the wonders of the universe by extending our senses with sophisticated instruments. In space, our instruments attain a unique perspective from which to observe the Earth below and the cosmos above. Exotic objects, such as gamma-ray bursters and braided rings, and global physical processes, such as the ubiquitous mesoscale eddies in ocean currents, were revealed by the unique capabilities of space instrumentation. New discoveries almost always stimulate new investigations that require new sensory capabilities and lead to further discovery.

• **Complete worldwide patterns revealing the extent and variability of important features and phenomena on the Earth have been assembled.** Atmospheric trace species (e.g., ozone, carbon monoxide, particulates, and many others) were sampled only at isolated locations until just a decade ago. Now with observations from space we can begin to piece together global budgets of these important chemicals. Satellites have produced images showing the location and seasonal movement of ecosystem boundaries. GEOS-3 produced the first realization of the global geoid over the oceans, and Magsat mapped the Earth's magnetic field. Landsat has contributed the first global view of geologic structures. Landsat and other Earth remote sensing satellites provide abstracted information on regions of the world that were unmapped 20 years ago. Since 1960, weather patterns have been mapped by satellites and now represent a major tool in weather forecasting and its interpretation to millions of television viewers. Mineral and oil deposits are located and mapped with the aid of Landsat and SPOT.

• **Solar system probes have discovered new planetary bodies and unexpected phenomena throughout the solar system.** The Voyager missions discovered new moons and rings around the giant planets that had not been detected from the Earth. The Voyagers also discovered active volcanism on Io, bizarre and unexpected tectonics on icy satellites, a tenuous atmosphere and massive nitrogen polar caps on Triton, tilted and shifted magnetic fields on Uranus and Neptune, and other previously undetected phenomena. These discoveries and the accompanying images from planetary explorers stimulated wide public interest in the science and exploration of space.

• **Space is not a void, but is occupied by complex plasmas.** One of the first Earth satellites discovered the Van Allen radiation belts in 1958. Continuing exploration with spacecraft revolutionized our view of the Earth's environment above 200-km altitude. We have discovered much about the molecular complexity of interstellar and circumstellar environments. We now know that there is a region above the ionosphere consisting of an electrically conducting plasma permeated by the Earth's magnetic field. It is called the magnetosphere because its structure and many of its processes are controlled by the magnetic field. We have learned that other planets possess magnetospheres and that the Sun has a magnetosphere consisting of a hot (about one million degrees Kelvin), magnetized plasma flow (the solar wind) extending beyond the orbits of the planets and filling interplanetary space, forming a distinct cavity—the heliosphere—in the nearby interstellar medium.

• **Instruments in space have now covered almost the entire electromagnetic spectrum, prompting the discovery of new objects and new environments impossible to see in any other way. Through spacecraft surveys of the celestial sphere at X-ray, ultraviolet, and infrared wavelengths, we have cataloged more than 250,000 objects, many of which can be seen only from space.** Observations from rockets and satellites revealed the first black hole candidates by detecting the intense, variable X-rays created near the event horizons of these exotic objects. The Vela satellites, designed to monitor gamma-rays from clandestine nuclear tests, quickly discovered gamma-ray bursters, objects emitting bursts of gamma-rays lasting only a few seconds, whose exact nature remains undetermined after more than a decade of study. The first infrared sky survey discovered large, solid particles in orbit around ordinary stars, presumably remnants of an earlier era of planet formation, detectable only from space-borne telescopes and suggesting that planetary systems like our own are common in the galaxy. As each new window at X-ray, gamma-ray, and infrared wavelengths opened, new phenomena appeared with characteristics difficult or impossible to sense in any other way.

We have identified the earliest stages of star formation from their faint infrared emission. We know that almost every type of star, normal and extraordinary, loses mass through outflowing streams of matter at all stages of its evolution. Galaxies that emit 99 percent of their light at infrared wavelengths, quasars with strong X-ray emission, supernovae, novae, accretion disks around neutron stars, and black holes have all been discovered or studied from space. Without spacecraft bearing scientific instruments, these phenomena would remain unknown.

Understanding Processes—How Do Our Worlds Work?

Manifestations of physical laws in the universe occur through physical and chemical processes that transform and transfer material, energy, and momentum throughout natural systems. Spacecraft missions enable us to study processes in a number of ways impossible from the Earth's surface: by using wavelengths absorbed by the atmosphere, by investigating celestial objects and phenomena at close range or by direct sampling, and by gaining a global-scale view of terrestrial processes. In many cases, spacecraft observation aims not just at understanding how a particular process works. Rather, by examining systems not reproducible in a laboratory, (e.g., planetary rings, magnetospheres, and atmospheres), space investigations gain a deeper understanding of the underlying physical laws.

- **The first measurements of important and cyclical phenomena on Earth have been made from space.** The now famous antarctic ozone hole was observed in 1984 and confirmed by satellite imagery from Nimbus-7. With satellite measurements the spatial extent and magnitude of yearly changes were established. The yearly movements of both the antarctic and the arctic icepacks have now been tracked in a synoptic manner to reveal detailed patterns. We have also observed El Niño events, the effects of volcanoes on the stratosphere, and, even occasionally, human-caused pollution events. Tropical cyclones are now tracked from their spawning grounds to their landfall, with important consequent reduction in human disaster.
- **The view from space has provided a fundamental advance in understanding of the structure and dynamics of the Earth system.** Perhaps the most pervasive accomplishment of the space age began in 1960 with the launch of TIROS-1, the first weather satellite. The images pieced together from the first several passes of the satellite dramatically confirmed a view of atmospheric dynamics that previously had only been inferred. Now,

every evening, televisions throughout the world display the latest generation of satellite imagery of global and regional weather systems. Since the launch of TIROS-1, no hurricane has touched shore without being spotted and tracked well in advance. The combination of sea surface temperature and chlorophyll fields confirmed the widespread ocean phenomenon of mesoscale eddies, changing our thinking about energy transport in the oceans. Ocean color observations, at first a curiosity recognized as useful only by fishermen, are now regarded as an excellent means to map mesoscale circulation patterns in the open ocean, especially where the temperature signal is washed out by seasonally high or low temperatures. That oceanic mesoscale features are widespread was firmly established by such measurements.

Understanding plate tectonics and the tectonics of other solid planets has revolutionized the study of the solid Earth. Space-borne measurements have contributed most spectacularly by establishing the rate at which plates move with respect to each other on the time scale of years and also by determining the geoid (the shape of the Earth's figure) with tremendously improved accuracy. The geoid relates to mass distribution in the Earth's interior and helps in showing how the Earth's mantle is convecting. Altimetry from orbit has improved understanding of both submarine topography and structure. Measurements from space have shown how the length of the Earth's day responds to wind currents on annual time scales and to interior movements on decennial scales. Precise distance measuring from space is revolutionizing the way we look at sea level variation on decennial time scales, and space-borne optical and infrared imagery has come to be essential in the study of the geology and geophysics of the continents. The first radar measurements from space show the enormous potential of that method, and magnetic measurements have established, among other things, that ultimately we can expect to monitor temporal variations in the Earth's main field from space on time scales from seconds to decades and centuries.

• **Enormous diversity in the manifestations of physical laws and processes on other worlds has been discovered through planetary exploration.** Solar system bodies are remarkably different in evolution, composition, and dynamics. Voyager encounters with the giant planets revealed intricate and unexpected complexity in the ring systems of Saturn, Uranus, and Neptune. Understanding the morphology of the rings has required detailed, ongoing studies at the forefront of gravitational dynamics. Much of this work has application to larger astrophysical systems, making ring studies a testbed for understanding gravitational dynamics.

Based on spacecraft observations, comparative studies of atmospheric dynamics on terrestrial and giant planets reveal a much broader range of physical conditions than those seen on the Earth, and outstanding problems remain that tax our understanding of the fluid mechanics of atmospheres. These include the maintenance of long-lived spot features on Jupiter, the origin of wind speed distribution on giant planets, and the energy balance of the Venus thermosphere. Tectonic processes occur on large and small bodies alike, and understanding both the energy sources and the origin of particular features continues to be a challenge long after they were identified by spacecraft. The thick atmosphere of Titan, discovered by Voyager, appears to hide a wealth of chemical and dynamical processes as complex as those on the Earth (including a methane "hydrological" cycle). Triton was shown by Voyager to have a surface-atmosphere nitrogen transport cycle akin to that of carbon dioxide on Mars, but with the added feature of nitrogen geysers, for which no Martian analog exists.

• **Microgravity has pronounced effects on living systems.** While plants and animals, including humans, can survive in the space environment, there are clear effects (including exposure to microgravity) that have pronounced impacts on living systems. Seeds of higher plants germinate in space, and grow at least into seedlings. Fertilized frog eggs have developed in space.

Understanding Origins—How Did Our Worlds Come to Be?

In the broadest sense, we seek to understand where we came from and how the natural world was formed. Questions about the origin of the universe, the formation of the solar system, and the appearance of life have been central to space research over the past three decades.

• **The cosmic background radiation seen from space is the signature of the beginning of the universe.** Cosmic background radiation is the oldest remnant of the early universe directly detected today. Its spectrum and pattern on the sky show us the most primitive state of matter and serve as the strongest constraints on our theories of how galaxies formed after the Big Bang. Between the discovery of cosmic background radiation in 1965 and 1990, observations from the ground, from aircraft, and from balloons all provided estimates of the spectrum of this very faint radiation. But the Cosmic Background Explorer (COBE), launched in late 1989, measured the spectrum so accurately that it disproved a few key results from the previous 10 years, and several hundred theoretical papers became meaningless. Midway through its mission at the time of this writing, COBE has already revolutionized our understanding of the early universe and promises the greatest refinement to our knowledge of the cosmic background since its discovery 25 years ago.

• **Solar system exploration revealed intricate links between the physical and chemical record of planetary bodies and the large-scale processes of star and planet formation.** Detailed Pioneer and Voyager studies of the outer system have shown that Jupiter and Saturn contain cores of elements heavier than hydrogen and helium, while Uranus and Neptune appear to be made of such cores with a veneer of hydrogen and helium. It is now recognized that the formation of these planets required accretion of ice and rock cores before gas was added. This is distinctly different from the formation of stars and constrains the evolution of the protoplanetary disk in a number of intriguing ways. The volatile composition of outer solar system bodies, including comets, is now just beginning to be elucidated and has a number of significant differences from the composition of environments in giant molecular clouds. With such a record, it is becoming possible to piece together a history of grain material from such clouds, through infall into the protoplanetary nebula and accretion into solar system bodies. Further missions to investigate in situ the less-evolved bodies of the solar system should clarify the history of the material that eventually formed the planets and allow us to characterize the formation of the solar system as a part of star formation and galactic chemical evolution.

- **Study of the gravito-electrodynamics in "dusty plasmas" discovered in Saturn's rings provided insight into the formation and evolution of the solar system.** Observations of spokes in Saturn's rings by Voyager highlighted the effect of electromagnetic forces on charged dust particles. In a similar way, the interaction of dust and plasmas in comets is believed to be a central element in understanding the formation of comet tails. Such observations have given rise to the study of gravito-electrodynamics in dust plasmas, which has important applications to the understanding of the formation and evolution of the solar system.
- **The search for life on Mars is of continuing scientific interest.** While signs of life were not found at the sample areas, evidence from Viking for past climate change on Mars shifts the issue to whether life formed on Mars sometime in the past and whether it exists in selected niches today. The answers to these questions are of fundamental importance, since on the Earth the evidence is strong that life heavily modified the Earth's environment in favor of continued habitability. If life actually formed there, why did this not occur on Mars?

Understanding Change—How Do Our Worlds Evolve?

Scientific events often remind us that few things are constant. The universe evolved from some primordial event or juncture and continues to evolve. Stars are born and die. Our Sun changes both gradually and cyclically. Planets develop climates, and then those climates change. We know from geologic records that the Earth has changed and continues to change. Some changes can be seen only from space by observations in new spectral ranges, by visiting our neighbors in the solar system, and by viewing our planet from the vantage point of Earth orbit.

• **Satellites now routinely document the extent of some major changes in the planet Earth.** Images from space document continuing change of the Earth's surface. The expansion of arid regions (desertification) is now tracked in several regions almost exclusively by satellite. Retreats of glaciers, deforestation and natural movements of forest edges, and even changes in habitat are now tracked from satellites in some locations. Space geodesy provides measurements of continental drift and changes in sea level.

• **Climate change on the terrestrial planets Venus and Mars is profound on long and short time scales.** Mariner 9 and Viking orbiters and landers have revealed the complexities of the Martian environment, with intricate weather patterns on diurnal and seasonal time scales distinct from those of the Earth. The absence of oceans and the presence of seasonal polar caps with which the atmosphere is in equilibrium provide a different physical system in which to test our understanding of climate from local to global scales. Viking and Mariner data detected seasonal and permanent polar cap composition, pressure variations at two ground sites, water vapor distribution, growth and decay of dust storms, and the presence of dust devils and mesoscale cyclonic storm systems. Evidence for an earlier, warmer climate on Mars based on Viking images of apparent river channels and glacial and lake deposits is even more profound. The evolutionary sequence leading from the warmer, wetter past climate to the present cold, dry climate is an outstanding issue raised by spacecraft exploration of Mars. The climate of Venus varies on the short term, as revealed by Pioneer Venus ultraviolet data showing a decrease in sulfur dioxide abundance in the stratosphere. The high surface temperatures on Venus, established firmly by spacecraft, constitute a dramatic demonstration of greenhouse warming. Magellan images indicate that Venus has had a violent, volcanically active history, the climatic implications of which have just begun to be assessed.

• **The solar energy flux is not constant, but varies with time.** Using knowledge gained over the past 30 years, we can now identify some of the physical mechanisms linking the Sun to the near-Earth environment. Motions in the convective layers of the Sun are believed to generate the magnetic field and solar wind variations; these in turn affect the Earth's magnetosphere and regulate the amount of plasma energy incident on the Earth's polar caps. Current research suggests that small percentage changes (about 0.5 percent) in the total energy output of the Sun (the solar constant) may influence short-term terrestrial climate. The Earth and its space environment contain coupled phenomena that must be studied as part of a system including the Sun and its plasma environment along with the Earth's magnetosphere, atmosphere, oceans, and biota.

Understanding Human Interaction—How Do We Affect and How Are We Affected by Our Worlds?

Space research is increasingly concerned with human activities. Information from Earth-observing satellites documents how human activities, including agriculture, forestation and deforestation, and the use of fossil fuels, are changing the Earth's surface and the planetary environment. Such information is used in a variety of applications to guide our activities. Spaceflight exposes humans to an unfamiliar environment with weightlessness and the threat of lethal streams of radiation, thus raising questions about human physiology that must be addressed to ensure safe, long-duration spaceflight.

• **Satellite observations are important for following some human impacts on the planet and are materially aiding many human endeavors.** The first nighttime picture of city lights provided from the Defense Military Satellite Program (DMSP) was a stunning image. More recently, leaders of several developing countries have been convinced by satellite imagery to control deforestation in tropical rain forests. In general, it is possible to track land use patterns on regional scales simply and easily with data from operational satellites. Even day-to-day logistical operations are aided by both Landsat and the Global Positioning System (GPS), as dramatically demonstrated in Desert Storm operations in 1990-1991.

• **People can live and work in microgravity for periods at least as long as one year and can then return to the Earth and readapt to gravity.** Perhaps the most striking accomplishment of the U.S. space program is the discovery that humans can work in space and on another body in the solar system and can travel to another part of our solar system and return successfully. Experience gained by the Soviets using their space station MIR has proven that humans can survive for up to one year in space and successfully adapt to 1 *g* upon return to the Earth. Such demonstrations have opened the way for human exploration beyond the Earth for centuries to come.

Prior to the spaceflight of higher mammals, physiologists did not know whether humans could survive for a significant period in a gravity-free environment. In microgravity, essentially all physiological systems are perturbed. Some systems, such as the bone and muscle, vestibular, and cardiovascular systems, are affected more than others, such as the gastrointestinal and urinary systems. Some systems, including the vestibular, adapt in a few days, whereas bone resorption continues at least for months and perhaps indefinitely.

• **Space plasmas can have a profound and sometimes disastrous effect on spacecraft and humans.** It is well established that many spacecraft systems and subsystems exhibit anomalies, or even failures, under the influence of magnetospheric substorms, geomagnetic storms, and solar flares. Processes such as spacecraft charging and "single-event upsets" (due to highly ionizing energetic particles) in processor memories make the day-to-day operation of space systems difficult. Radiation from these events could be fatal to humans if adequate protection is not provided.

PROSPECTS AND OPPORTUNITIES FOR SPACE RESEARCH

Almost every field touched by space science has planned missions or long-term opportunities promising major advances in our scientific knowledge of the universe near and far. The major missions have been thoroughly reviewed and refined. And the flow of novel ideas and proposals for small projects in unexplored areas continues as the scientific achievements of the last three decades stimulate new questions. The following is a representative list and brief description of the myriad of missions and initiatives that are under discussion or planned for launch. The list is not exhaustive but illustrative of the many exciting opportunities that exist.

- **Earth Observing System (EOS).** The EOS will make a range of contributions to the scientific questions outlined in the federal Global Change Research Program. For some key questions, such as the role of clouds in the planetary radiation budget and in the global hydrologic cycle, EOS will provide information essential to rapid advancement in understanding the planet. In other areas, like the Earth's history, EOS will supplement information largely derived from surface measurements (e.g., sequencing of landforms). In all, EOS is the centerpiece of the measurement program for global change research. Instruments proven for scientific purposes on EOS will be the next generation of operational sensors to monitor our weather, land use, and changing environment.[1]
- **Specialized spaceflights for measuring earth processes—Earth Probes.** Not all of the important variables will be measured from EOS. A number of special initiatives are planned as Earth Probes. These include Synthetic Aperture Radar (SAR), the best hope for quantitative measurements of soil moisture and vegetative mass; the Tropical Rainfall Measuring Mission (TRMM); the Sea-viewing Wide Field-of-View Sensor (SeaWIFS), for studying oceanic biomass and mesoscale circulation features; a scatterometer to investigate global wind fields over the ocean; and new magnetic and gravity measurements.
- **Geosynchronous platforms for Mission to Planet Earth.** These satellites will provide continuing detailed observations of a number of variables in mid-latitude with temporal resolution of minutes (versus days). They will contribute to studies of atmospheric dynamics, oceanic dynamics,

atmospheric structure, water vapor, surface features and vegetation, and many more processes. Some of these satellites will provide all-weather observations by using microwave emissions.

• **Upper atmosphere composition and dynamics—UARS.** Launched in late 1991, the Upper Atmosphere Research Satellite (UARS) is to measure the key constituents and key dynamic processes of the upper atmosphere on a global scale. UARS will also contribute to studies of ozone depletion.

• **Ocean topography mission—TOPEX/Poseidon.** Planned for a 1992 launch, the TOPEX/Poseidon spacecraft will resolve topography in order to measure the variable component of oceanic circulation. In due course (with a gravity mission), it will produce a quantitative measure of mean oceanic circulation.

• **Improved operational meteorological satellites.** Continuing improvements are planned for the U.S. series of weather satellites to enhance observations of the horizontal and vertical structure of the atmosphere (mainly temperature and water content) worldwide. These observations will contribute to improved forecasts of large-scale weather patterns and significant weather events affecting human activities.

• **Operational land observatories—Landsat.** Many routine remote sensing applications require continuing and consistent measurements. These have been provided by Landsat, and more recently by SPOT. Applications include mineral exploration, agriculture, and land use management.

• **Martian climatic processes—Mars Observer.** The Mars observer will provide a comprehensive remote sensing study of the surface and atmosphere, with emphasis on climate change on a variety of scales.

• **Aeronomy of the Martian atmosphere—Mars Aeronomy Observer.** The Mars Aeronomy Observer will characterize the potential fields of the upper Martian atmosphere, clarify the role of photochemistry, and study the dynamics of the ionosphere.

• **Geophysics of the Martian surface—Mars penetrators.** These missions will install a network of seismometers, weather stations, and heat flow experiments on the Martian surface and possibly perform simple geochemical analyses.

• **Study of the Jovian System—Galileo.** Galileo, now en route to Jupiter, will deploy a probe to measure directly the composition and dynamics of the Jovian atmosphere and will study in detail the satellites, atmosphere, and magnetosphere of the Jovian system.

• **Detailed geophysical surveys of the Galilean satellites—The Jupiter Grand Tour.** This nuclear electronic propulsion mission will orbit each individual Galilean satellite, providing microwave and radar sounding of the subsurface. It will deploy penetrators for surface geochemical analyses of selected satellites and provide global remote sensing for each from the main spacecraft. It will determine gravitational moments and hence the constraints on internal structure for each satellite.

• **Origin and evolution of the outer solar system—CRAF/Cassini.** Planned for launches in the late 1990s, these missions will closely observe the nucleus of a comet, deploy a probe into the atmosphere of Titan, and provide in-depth physical and chemical studies of primitive bodies, Titan, and the Saturn system. The surface atmosphere processes appear to be as rich and complex as those on Earth but without the presence of life.

• **Neptune Orbiter and Probes—Triton penetrator and Pluto flyby—Poseidon.** This spacecraft will orbit Neptune and drop a probe to sample gas abundance and atmospheric dynamics through and below the ammonium hydrosulfide cloud layer. It will perform long-term atmospheric observations from orbit. The orbiter will make repeated passes by Triton to determine surface temperature distribution, volatile transport processes, gravitational moments (for internal structure), and atmospheric composition for molecular abundances, including noble gases. A companion probe to make the first flyby of the enigmatic Pluto-Chalon system is also under study.

• **Intensive geological and biological studies of sites on Mars—Mars Rover and Sample Return.** Mars Rover is being planned to conduct detailed, on-site geological and biological investigations of portions of the Martian surface. It will search for microfossils and return selected samples to the Earth for comprehensive laboratory studies.

• **Detailed atmospheric and surface chemical analysis for Venus—Venus Probe.** The Venus Probe will determine the isotopic and chemical composition of the atmosphere, resolving ambiguities from previous experiments. It will characterize the geochemistry of uplands and plains sites on the surface.

• **Comet Sample Return—Rosetta.** Rosetta is intended to collect a sample of a comet nucleus from at least 1-meter depth, in order to understand further the ice-volatile component. The sample will be preserved and returned to the Earth for laboratory study.

• **Global mapping of the lunar surface—Lunar Observer.** The Lunar Observer will characterize the crustal composition of the Moon, place lunar samples in global context, and search for ice in the polar regions of the Moon.

• **Composition and properties of a sample of asteroids—Multiple Asteroid Rendezvous Mission.** This mission is intended to yield observations of remotely sensed asteroid surface composition as a function of heliocentric distance.

• **Exploration of the universe through new windows—The Great Observatories.** The major components of the planned astronomical satellites for the next decade are NASA's Great Observatories, four orbiting platforms for observations in different wavelength bands. The first of these, the Hubble Space Telescope (HST) now flying, was designed to improve the resolution, sensitivity, and wavelength range of ultraviolet and visual observations beyond anything available from the ground. With modifications to its camera optics to compensate for spherical aberration induced by construction errors, it should achieve this full resolution by 1993. The Advanced X-ray Astronomy Facility (AXAF) will increase the capabilities of X-ray observations by several orders of magnitude over any previously available, allowing study of accretion disks around black holes, quasars, and the diffuse X-rays from distant clusters of galaxies. The Gamma-ray Observatory (GRO) is designed to study the exotic gamma-ray bursters as well as the matter-antimatter annihilation seen toward the center of the galaxy. The Space Infrared Telescope Facility (SIRTF) will cover the entire infrared spectrum from 1 micron to almost 1 millimeter, searching for dark matter in the form of brown dwarfs, the birth of new planetary systems around young stars, and the first generation of galaxies created after the Big Bang.

• **Other astronomical missions.** A suite of other missions is equally important for exploration of emissions impossible to study from the ground. The Extreme Ultraviolet Explorer (EUVE), the X-ray Timing Explorer (XTE), and the Submillimeter Wave Astronomy satellite are three examples among many. These special-purpose satellites will further extend our capabilities by providing, for example, high spectral resolution in special bands, wide field coverage, special timing capability to detect rapid variables and accurately measure their periods, polarization properties of light, particle detectors for cosmic rays, and specialized instruments to follow up new discoveries with the Great Observatories. Suborbital observations, including the Stratospheric Observatory for Infrared Astronomy (SOFIA) measurements from aircraft, are essential complements to the spacecraft missions. They not only provide unique capabilities, but also aid space instrument designers by allowing quick turnaround and hands-on development of novel techniques.

• **Moon-based instruments.** Multiple-telescope interferometers in Earth orbit or on the Moon promise to improve the angular resolution for visual and infrared observations by several orders of magnitude. At this time, spacecraft interferometers, both for imaging and for astrometry, represent one of the logical next steps for instrument development. It is widely believed that advances from this technique alone could revolutionize our view of the universe with resolution fine enough to image surfaces of nearby stars and probe to the event horizons of massive black holes in the nuclei of distant galaxies.

• **International Solar-Terrestrial Physics (ISTP) Program.** A constellation of several Earth-orbiting satellites will be launched during the 1990s by the United States, Japan, Europe (through the European Space

Agency) and the [former] USSR. The overall scientific objective of ISTP is to develop a comprehensive, global understanding of the generation and flow of energy from the Sun, through the interplanetary medium, and into the Earth's space environment. The improved knowledge will have practical applications in understanding and forecasting radio and power interruptions from solar events.

- **Orbiting Solar Laboratory (OSL).** The OSL is intended to provide high-spatial-resolution measurements of temperatures, densities, velocities, magnetic fields, and chemical abundances in the solar atmosphere to determine the fundamental processes responsible for plasma heating and the transport of mass and energy between different levels of the solar atmosphere.
- **Solar Probe.** This spacecraft will pass through the outer regions of the Sun's corona, carrying out in situ measurements of plasma, fields, and energetic particles in the solar wind acceleration region.
- **Imaging Super Cluster (ISC).** Two spacecraft in highly elliptical polar and equatorial Earth orbits will employ photon, energetic neutral atom (ENA), and radio-wave imaging techniques to provide images of the Earth's radiation belts (Van Allen belts) and magnetotail. A cluster of four spacecraft will be actively maneuvered throughout the magnetotail to make simultaneous in situ plasma and field measurements.
- **Ionosphere-Thermosphere-Magnetosphere Coupler (ITMC).** A constellation of several Earth-orbiting satellites will investigate the physical, chemical, dynamic, radiative, and energetic processes that couple the ionosphere-thermosphere-magnetosphere system with the heliosphere and outer magnetosphere above and the stratosphere below.
- **Mercury Orbiter (MEO).** Two spacecraft with instruments to observe plasmas and fields and with solar physics and planetology experiments will fly in polar orbit around Mercury. The mission will map the magnetic structure and plasma environment of Mercury, investigate apparent substorm processes, and study the transfer of mass and energy from the solar wind.
- **High-Energy Solar Physics (HESP) Mission.** This mission will acquire high-resolution imaging and spectroscopy of high-energy radiations during solar maximum. Sub-arc-second imaging and high-resolution gamma-ray spectroscopy will provide simultaneous photospheric and coronal imaging.
- **Long-duration human exposure to microgravity.** The effects of microgravity on physiological systems that have evolved in the constant and ubiquitous presence of gravity provide rich opportunities for research. Understanding of the processes of physiological systems is facilitated by the study of perturbed systems, and the reduction of gravity provides such an effect. Much remains to be discovered and understood. Such studies are a necessary prelude to defining limiting physiological factors for long voy-

ages in space. Experiments need to be conducted in microgravity for at least as long as the contemplated voyage.

• **Human productivity in space.** We do not know whether crew members can withstand the effects of long-duration space missions of several years or more. Much basic and applied research is necessary to ascertain whether spaceship design and programming of activities can enhance the safety, efficiency, and accomplishments of crews on long-duration missions. The social effects of long-term confinement are unknown, but such confinement can be provided on the Earth. Very-long-term studies will be required. These should be started several decades before a long-term human mission is designed in detail. As with EOS, practical applications are likely to develop quickly based on the improved measurements and the enhanced understanding they generate.

• **Effects at varying gravity—space-based centrifuge.** Variable speed centrifuges in space will permit quantitative assessment of effects of different accelerations on physiological functions. Studies at 1 *g* either on the Earth or in a centrifuge in space would provide control states for comparison with microgravity environments. A centrifuge large enough to provide a living environment for crew members would permit determination of the extent to which constant acceleration can prevent or attenuate the physiological disturbances in space, especially those of bone and muscle. Even prolonged vigorous exercise has, at most, only limited effectiveness in microgravity.

• **Reproduction in microgravity.** Prolonged sojourns in space will provide the opportunity to determine whether sequential generations of higher plants and animals will occur in the absence of gravity.

Table 2.1 shows how many of these and other initiatives and programs contribute in a major way to addressing the five questions used above in this chapter to organize the exposition of past accomplishments of the U.S. space research program. Major missions and smaller missions, of course, contribute to many questions simultaneously. Other initiatives often focus on just one of these areas.

The scientific potential of the planned programs is tremendous. They are well planned and have been reviewed by scientists at many different levels, each group reaffirming their worth to science. When the small, less visible programs and the unseen opportunities that will arise from rapid advances in technology and scientific understanding are added to this list, the prospects are far greater than the support that will be available.

As this list of prospects demonstrates, we must grapple with choices between large projects and small, between projects in different fields, and between support for mature fields versus support for untested ideas. To succeed in space research, we must push forward with new missions while

TABLE 2.1 Major Contributions of Future Initiatives and Programs to the "Large Questions"

Initiatives and Programs	Major Contributions				
	Discovery	Understanding Processes	Understanding Origins	Understanding Change	Understanding Human Interaction
Research and Analysis Base	X	X	X	X	X
Mission to Planet Earth					
EOS	X	X		X	X
Earth Probes	X	X			
Geosynchronous platforms		X			
UARS	X	X		X	X
TOPEX/ Poseidon		X			
Upgraded meteorological satellites		X			
Landsat/SPOT	X	X		X	X
Planetary and Lunar Exploration					
Mars Observer, Mars Aeronomy Observer, and Mars penetrators		X		X	
CRAF		X	X	X	
Cassini	X	X	X	X	
Galileo	X	X	X		
Poseidon	X	X	X	X	
Mars Rover and Sample Return	X	X		X	
Venus Probe		X		X	
Rosetta	X		X		
Lunar Observer		X	X		
Astronomy and Astrophysics					
Great Observatories	X	X	X	X	

continued

TABLE 2.1 *Continued*

Initiatives and Programs	Major Contributions: Discovery	Understanding Processes	Understanding Origins	Understanding Change	Understanding Human Interaction
Other Astronomical Missions					
EUVE	X	X			
Submillimeter wave astronomy	X		X		
XTE	X	X		X	
Moon-based imaging interferometry	X	X	X	X	
Grand Tour Cluster		X		X	
Space Plasma Physics					
International Solar Terrestrial Physics (ISTP) Program		X	X	X	
Orbiting Solar Laboratory (OSL)		X		X	X
Solar Probe	X	X	X		X
Mesosphere Lower Thermosphere (TIMED)		X		X	X
Inner Magnetosphere Imager (IMI)		X		X	
Ionosphere-Thermosphere-Magnetosphere Coupler (ITMC)		X		X	X
Mercury Orbiter (MEO)	X	X			
High-Energy Solar Physics (HESP)	X	X	X		
Biological Systems in Space					
LifeSat		X			X
Spacelabs/Space Shuttle		X			X
Space Station		X			X

reinvesting in human resources and the technology base necessary to maintain vigorous scientific enterprise.

LESSONS LEARNED

Many lessons are available from more than 30 years of experience in flying space research missions. Here they are coalesced into a few specific statements offered as guidance for the future:

- **Routine access to space is of utmost importance to scientific research in space.** Unfortunately, this *does* need to be said because space research has suffered from restricted access to space. Launch vehicles should be appropriate for the mission and should reliably achieve the needed orbit and launch date.
- **The space program should minimize its reliance on a single launch capability.** The main example of a failure to follow this principle is the forcing of all payloads onto the Shuttle. However, scientific research programs should also avoid excessive reliance on large, complex spacecraft. Space research requires a balance of large and small missions. The following two lessons are related to this one.
- **Build spacecraft with robustness and flexibility.** The Voyager spacecraft operated beyond their lifetimes, permitting scientifically exciting extended missions to Uranus and Neptune. Relatively inexpensive upgrades to Earth-based communication antennas maximized the data return from these most distant planets.
- **Do not force scientific activities into an inappropriate approach.** A prime example is the forcing of Hubble onto the Shuttle, with the consequence that it was required to operate in low Earth orbit and to be "man rated." These requirements diminished its scientific effectiveness, raised its costs, and increased its operational complexity by large factors.
- **In almost all cases of interest, space-based scientific investigations must be complemented by other observations.** For example, in the Earth sciences, surface verification of space measurements is essential. The Great Observatories cannot make all needed observations: the light-gathering capacity of large ground-based telescopes is needed for spectroscopy.
- **For the lifetime of scientific programs, scientists should be intimately involved with the instruments making the observations.** This lesson has several implications. For example, the principal investigator of the Solar Mesosphere Explorer was intimately involved with its development and operation and that was seen as contributing strongly to its scientific, schedule, and budget success. Another implication is that there must be continuous efforts to make data readily available to the scientists who

will use it. An unfortunate example of the failure to do this is the filtering (by data management algorithm) of data on ozone concentrations, which delayed discovery of the antarctic ozone hole. A positive example of successful efforts to make data available is the unplanned use of Advanced Very High Resolution Radiometer (AVHRR) data to determine a global vegetation index. These data were intended only for cloud images and sea surface temperature maps.

• **Adequately fund data analysis.** Seasat is an example of a program that had grossly inadequate funding for data analysis, and the result was great delay of scientific results. A positive example is found in astronomy, where funds are available to do research using archived data. When proposals to use a certain data base are no longer being submitted, then those data probably have been adequately exploited for the time being.

• **There is a need for more accountability in project management.** The Earth Radiation Budget Experiment (ERBE) is an example in which two centers had partial responsibility for a project. It was badly managed until responsibility was clarified. On the other hand, the Upper Atmosphere Research Satellite (UARS) project was not started until responsibilities were clear. In addition, the UARS managers made a careful cost estimate at the beginning, and the project has remained within that budget. Because the ultimate purpose is scientific research, one way to ensure accountability in science missions is to put scientists in charge. Another caveat with respect to project management accountability is that promises must be linked to reality. A primary example of the failure to do this was the claim that the Shuttle could be expected to fly 50 missions per year.

• **Multiyear funding of basic research supporting spaceflight activities is essential.** The development of new concepts and the exploitation of observations from space missions are both multiyear efforts and usually involve graduate students working on dissertations. Annual proposals and multiple grants take time and effort away from research and seriously impede progress.

• **Basic research is a good investment.** The fruits of space research are harvested by analysis of observations and modeling, efforts that reveal new opportunities for observation. When resources are severely limited, the best value is obtained from basic research, as supported by the research and analysis program, because it maintains the vigor of scientific research and education and provides the foundation for future scientific progress.

• **Consensus works.** When a community can say with one voice what needs to be done, it can have great force in budget and program planning. Two examples are the sequence of astronomy survey reports[2] and the report of the federal Committee on Earth Sciences setting forth a national global change research program.[3]

NOTES

1. For additional National Research Council discussions on EOS, see Space Studies Board, "Space Studies Board Position on the NASA Earth Observing System" (unpublished report issued July 10, 1991) and the 1990 report of the Panel to Review the FY 1991 Global Change Research Program, *The U.S. Global Change Research Program: An Assessment of FY 1991 Plans* (National Academy Press, Washington, D.C., 1990).

2. See, for example, the two most recent such surveys (National Academy Press, Washington, D.C.): Astronomy Survey Committee, *Astronomy and Astrophysics for the 1980's* (1982); Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, *The Decade of Discovery in Astronomy and Astrophysics* (1991).

3. Committee on Earth Sciences. 1989. *Our Changing Planet: A U.S. Strategy for Global Change Research*, a report to accompany the U.S. President's Fiscal Year 1990 Budget.

3

Today's Imperatives

The nation's overall agenda in science and technology, including scientific research in space and the space program, serves the highest national purposes, including the development of new understanding about our surroundings and the maintenance of national vitality. This chapter examines contemporary imperatives—largely external to science and space research—and describes their implications for space research and the civil space program.

INTERNATIONAL COMPETITION AND CONCERNS

Rapidly evolving relationships between the leading nations of the world are now characterized by the movement from ideological and military competition to economic and technological competition.

The Challenges

From the 1940s until very recently, diplomatic and military competition between West and East dominated international affairs. This competition shaped national priorities and, in turn, national budgets, major initiatives in science, engineering, and technology, and efforts to win friends among other nations. Some of the old alliances and international political structures constructed in response to this competition have unraveled, and nations are engaged in long-term reallocation of funds between defense and other national endeavors.

The United States now has strong competitors in the economic and technological realm to replace the single nation dominant in military competition. Other nations are entering the arena; new alliances based on economic and geographical imperatives promise to be powerful contestants. The complexity of the new competition is compounded by the fact that the world now has a geographically integrated economy. The flow of information and investment funds ignores national boundaries. In this new economy, new strategies are indicated.

In the midst of this new global economic competition, there is a growing worldwide concern for the environment. Human activities are changing the surface and atmosphere of the planet, and the full consequences of these changes are still unknown. The world will look to science and engineering to help solve these problems, which have been created in part by technology and in part by a burgeoning human population. Assessing the gravity of the threat and determining the rapidity with which we should act require much more information about the Earth and how it functions.

The Response

Intellectual capacity, creativity, and flexibility are critical capabilities for coping with complexity in science and national affairs. Because of its nature, the U.S. system should respond well to change and complexity. Our decentralized system permits many independent initiatives to flourish simultaneously. It creates flexibility and encourages intellectual creativity to take advantage of opportunities. We should be a nimble competitor, thriving on change.

This nation should emphasize its unique strengths: heterogeneity, decentralized capabilities, individual initiative, and fondness for competition. We need to exploit our diverse skills, strengthen the education of our children, and emphasize continuing education and intellectual revitalization. We can take advantage of the university system as a key component of national science capability and encourage industries to participate in basic research and thus strengthen the national science infrastructure.

We need to focus our response to the new global economic competition. The export of products and services that are based on knowledge and sophisticated technology may be more profitable and may confer more influence than the export of traditional manufactured goods. This nation should emphasize those areas with the largest potential net national benefits—the activities in which knowledge, information, and sophisticated management of processes are dominant. Space research and the overall space program can contribute significantly to such an emphasis.

As a nation, we need a strong sense of what is really important in our rapidly changing world. In scientific research, and in the space program, we need to create a way of determining priorities among initiatives that blends scientific opportunities with national imperatives. Having done that, we should be able to formulate effective programs and initiatives and implement them surely, swiftly, and successfully.

DOMESTIC POLITICS

For space research and for the space program, the reality of domestic politics is that the federal budget is both finite and in deficit. The nation cannot afford to do all the things that it could or should. Choices must be made. The long-term reign of national defense as a top priority for federal spending may be ending, but there will be continued strong competition from other areas and other initiatives for increased funds.

In recent years, science generally and scientific research in space in particular have fared well despite varying political agendas and eccentricities of the budget process in which they compete. Presidents have consistently recommended increased funds for science as an investment in enhanced economic competitiveness. In the congressional appropriations process, however, much civilian science and the space program are in direct competition with the social programs of agencies concerned with housing, health, the environment, and veterans' affairs, all of which must be funded within a single budget allotment.

As part of the vigorous public debate about the relative needs of our society and the discussions over appropriate national goals, there is an opportunity for scientific space research and the entire space program to develop a compelling, long-term agenda that will be seen as rational and equitable by the interested constituencies. Certain ingredients are critical for success. There must be consensus among scientists on the relative priorities of the major initiatives. In addition, the agenda must respond to the needs of the nation as well as to opportunities presented by scientific progress.

For more than four decades, science and the government have operated largely under the terms of the social contract envisioned by Vannevar Bush in 1945 in *Science—The Endless Frontier*.[1] Bush argued that science, supported by federal funds and allowed to make its own decisions, would produce benefits for the public. Now the contract seems to be changing. Expected benefits need to be specified more clearly, and actual performance is more likely to be reviewed to determine whether claimed benefits have been realized. There is an increasing expectation that scientific progress should be linked more directly to economic benefit and competitiveness as part of the justification for receiving federal funding. Universities and other not-for-profit research institutions are seeking to transfer intellectual property to the private sector, partly to support economic vitality and partly to create an independent source of funds. Thus there are pressures today to convert scientific results into useful products through entrepreneurial initiative and direct management of the transfer process. In addition, there is a growing demand for an agenda, for a system of priorities in scientific research and for scientific initiatives.

ECONOMIC REALITIES AND THE MANAGEMENT OF AVAILABLE RESOURCES

Economic determinants are increasingly important in the formulation of public policy and provision of funds supporting science. The demands for clear benefits from public investments and for effective use of available resources confront the space science and applications community today.

Valuation of Space Research—Assessing the Benefits

Two trends in public policy offer both challenge and opportunity to space science. First, there appears to be an increased willingness to support activities producing primarily broad social benefits, as evidenced by policy and action motivated by concerns for clean water and clean air, for protecting the environment, and for maintaining wilderness, wildlife, and habitats. There is some evidence of heightened public interest in space activities, particularly to augment scientific understanding.[2] Second, there is an increasing demand for publicly supported activities to provide explicit evidence that the benefits to be achieved outweigh the costs. Responding to these demands requires careful thought to specify how space research that fundamentally serves to augment knowledge and understanding contributes to society; it requires careful analysis to answer questions such as, In what way and by how much does space research further national objectives?

Contributions of Space Research to Knowledge and Understanding

Enhancement of knowledge through scientific research has been recognized for nearly 50 years as a national imperative meriting federal financial support. The National Aeronautics and Space Act of 1958 sets forth the objective to extend "human knowledge of the Earth and of phenomena in the atmosphere and in space." The President reiterated this commitment in stating that an objective of the U.S. civil space activities "shall be . . . to expand knowledge of the Earth, its environment, the solar system, and the universe. . . ."[3]

The overall goal of science is to garner sufficient information to develop understanding of the structure and evolution of objects or phenomena in the natural world. Science seeks to create an understanding sufficiently robust that correct predictions can be made about objects or phenomena not yet observed. Science thus expands our perceptions and, in some cases, enhances our control of natural phenomena or allows us to modify our relationship with our environment. The recent progress of science is characterized by expansion of temporal and spatial domains of interest, by enhanced awareness of the complexity of interactions in the natural world, and by an increased ability to provide quantitative measures and models of natural phenomena. In this sense, space research contributes markedly to scientific progress, as is shown in Chapter 2.

Clarifying the significance of science or of space research as a contributor of enhanced knowledge and understanding will be an important consideration in any attempt to create an agenda for science. It behooves scientists seeking public support to demonstrate to the public and its representatives that the fruits of scientific research do indeed enhance the quality of life and the welfare of the nation's citizens.

Evaluation of Other Benefits of Space Research

For the foreseeable future, the space program and space research will compete for public support with other scientific and technological initiatives and programs offering a variety of social benefits, in some cases even competing with different approaches offering the same understanding or result. Table 3.1 illustrates several of these activities. Table 3.1a lists some of the major science initiatives proposed for the next decade or so. If national spending on nondefense research and development continues at the rate prevailing since the mid-1970s (see Table 3.2), projects in Table 3.1a alone will require a 50 percent increase in nondefense research and development funding. Additional initiatives or activities will require additional funding. The estimated costs of these projects are three times as large as the present total spending on basic research.

The difficulties faced by policymakers and the Congress are suggested by Tables 3.1b, c, and d, which illustrate the opportunity costs (that is, the alternatives) of spending public funds on science or space research. The activities in Tables 3.1b and d are significant in that they include programs that compete directly with space funding within the relevant congressional appropriations committees.

Economic benefits have been cited as a rationale for space research since the inception of the U.S. civil space program, yet precisely what is meant by "economic benefit" has not always been clear. The narrowest definition would include strictly commercial activity that is profitable in the business sense. The case most often cited is that of commercial communications satellites, where economic benefits can be defined as the value consumers place on the service and are measured by industry revenues.[4] For

TABLE 3.1 Spending Estimates for Various National Science, Technology, and Social Programs (1989 $billion)

(a) Proposed Major National Science and Technology Projects During the Next 15 Years

Project	Estimated Total Cost	Estimated Annual Cost[a]
Superconducting supercollider	8.0	0.5
Mapping human genome	3.0	0.2
Space Station	30.0	2.0
Manned mission to Mars	400.0	28.0
National aerospace plane	4.0	0.3
Earth Observing System	32.0	2.1
TOTAL	477.0	33.1

(b) Selected Social Programs (FY 1989)

Program	Estimated Annual Cost
Elementary, secondary, and vocational education	10.0
Higher education (financial assistance, student loans)	10.0
Social services (block grants, foster care, human development)	10.0
Housing assistance	10.0
Food and nutrition	21.0
TOTAL	61.0

(c) NASA Space Science Basic Research Program (FY 1989)

Budget Line	Estimated Annual Cost[b]
Physics and astronomy	0.25
Life sciences	0.05
Planetary exploration	0.20
Solid Earth observation	0.02
Environmental observation	0.13
Communications	0.01
TOTAL	0.66

(d) Selected Social Programs (FY 1989), Each with Budgets Commensurate with the Total of Table (c)

Budget Line	Estimated Annual Cost
Summer youth employment	0.7
Assistance to dislocated workers	0.5
Job Corps	0.7
Older Americans employment	0.3
Low-rent public housing	0.9
TOTAL	3.1

[a] Discounted current cost of project assuming 4 percent inflation and 15-year construction time.

[b] Adjusted from 1988 to 1989 dollars using implicit price deflator for 1989.

SOURCES: Table (a): Stever, G., and D. Bodde. 1989. "Space Policy: Deciding Where to Go," *Issues in Science and Technology* V, No. 3, pp. 66-71. Tables (b) and (d): *Budget of the U.S. Government, FY 1990* (U.S. Government Printing Office, Washington, D.C.). Table (c): Congressional Budget Office, U.S. Congress. 1988. *The NASA Program in the 1990's and Beyond* (CBO, Washington, D.C.), May.

TABLE 3.2 Trends in Federal Spending for Research and Development (current $billion)

Year	Defense	All Other	Total	Basic Research	GNP	Total/GNP (percent)	Basic/Total (percent)
1960	6.1	1.5	7.6	0.6	497	1.53	7.9
1965	7.3	7.3	14.6	1.4	657	2.2	9.6
1970	8.0	7.3	15.3	1.9	959	1.60	12.4
1975	9.7	9.3	19.0	2.6	1522	1.25	13.7
1980	15.1	14.7	29.8	4.7	2670	1.12	15.8
1985	33.4	16.1	49.5	7.8	3952	1.25	15.8
1986	36.5	16.2	52.6	8.1	4187	1.26	15.4
1987	38.4	17.6	56.1	9.0	4434	1.27	16.0
1988	39.5	19.3	58.8	9.5	4780	1.23	16.2
1989 (est.)	41.3	21.7	63.0	10.5	5120	1.23	16.7
1990 (est.)	44.0	23.3	67.3	11.2	5476	1.23	16.6

SOURCES: GNP Data, 1960 to 1970: *The Budget for FY 1980* (Executive Office, Washington, D.C., 1979), Table 19; GNP Data, 1975 to 1990: *The Budget for FY 1990* (Executive Office, Washington, D.C., 1989), Table 17; Research and Development data, all years, special analyses: *Budget of the United States Government, FY 1990* (Executive Office, Washington, D.C., 1989), Table J-10.

public policy, there are additional benefits and costs that must be considered, even for communications satellites. Broader definitions include contributions to technological progress, national prestige and competitiveness, and science and engineering education.

The task group does not offer a formal cost-benefit analysis[5] for scientific research in space because such an analysis lies beyond its charge and, perhaps more significantly, because it is relatively difficult to do. It is desirable to measure all costs and all benefits of an activity whether readily quantifiable or not, but in the case of scientific research in space many of its benefits and many of its costs are not easily observable and are difficult to measure. It should be noted that scientific research is not alone in having benefits and costs that are difficult to measure. Many public projects for the improvement of human health, safety, and environmental regulation are equally difficult to analyze in these terms. Table 3.3 lists but does not attempt to quantify those costs and benefits readily discernible in scientific research in space initiatives.

From the perspective of setting priorities for space research initiatives, however, many requirements of cost-benefit analysis are instructive. Both those who propose research initiatives and those who review them should

TABLE 3.3 Illustrative Benefits and Costs of Space Research Initiatives

Benefits	Costs
Expanded understanding of • structure and processes of physical world • origins and evolution of the Earth, solar system, and universe • human interactions with our surroundings	Costs of spacecraft, associated hardware, launch vehicles and services, and other facilities
Generation of technological progress and maintenance of national technological capability	Salaries, wages, costs of management and administration, and other overhead
Gain in world prestige (if successful)	Environmental degradation from space activities (e.g., space debris and launch site pollution)
Improved decision making and enhanced capabilities in public and private applications of space-derived information	Diversion of fiscal and human resources from other scientific and public programs
Stimulation of pride in discovery and research and the excitement of exploring the unknown	Loss in world prestige (if failure)
Improved public education and enhanced awareness of science and the world around us	
Improved capabilities for processing data and managing information	
Improved understanding of the scientific research process	
Support of graduate research and education and attraction of students at all levels to science and engineering	
Discovery of usable resources in solar system bodies	

NOTE: The benefits and costs shown here are merely illustrative. For more detailed discussion of benefit-cost approaches, see Musgrave, Richard, and Peggy Musgrave. 1989. *Public Finance in Theory and Practice* (McGraw-Hill, New York), and Rosen, Harvey S. 1989. *Public Finance* (Irwin, New York).

identify, as far as possible, all costs and benefits, to determine the necessary conditions for success, the probabilities and consequences of failure, and the expected outcomes. Such a process should improve proposals for initiatives. If such a formal analysis forces assumptions to be stated explicitly, they can be examined and compared with alternatives, and the possibilities for manipulation will be reduced. This analysis could provide for a formal comparison between initiatives when priorities are recommended, either within the community or as part of the federal budget process, and could clarify expected contributions of various initiatives. Those with the greatest scientific merit sometimes will have less immediate social benefit and practical utility; those with the greatest social benefit sometimes contribute less markedly to the enhancement of knowledge.[6] The issue thus becomes the relative weighting between enhancement of knowledge, provision of social benefits, and costs.

Comparison between initiatives in this way is important in distinguishing scientific research in space from other aspects of the space program. The scientific research community has long been uncomfortable with the justification of large-scale initiatives in the space program by their scientific motivations when their purpose is not scientific and opportunity costs preclude more fundamental scientific initiatives. Analysis of alternative initiatives should reveal this disparity and provide an incentive for structuring such programs to provide greater scientific benefit. It should also provide convincing support for the recommendation that "the advance of science and its application to human welfare be adopted and implemented as an objective no less central to the space program of the United States than any other. . . ."[7]

Although they can be identified and assessed, direct social benefits from scientific research in space and the overall space program are difficult to quantify. Success in space research has provided a stimulus for education, enhanced national prestige, and fostered public pride in national accomplishment. The public has demonstrated a continuing interest in space research and in information obtained about the Earth and other planets as well as the universe beyond. The Viking, Voyager, and Pioneer missions were widely publicized in both print and on television. The discovery of a defect in the mirror of the Hubble Space Telescope was a major news item. Recommendations of the Advisory Committee on the Future of the U.S. Space Program were featured in the headline article in many newspapers when they were released. Less obvious are space program contributions to technological development as a stimulant to economic progress; attempts to quantify them have been, so far, unconvincing. Still, the development of national capabilities for managing complex endeavors and for creating and managing information is an important benefit of the overall space program.

Effective Use of Space Research Resources

Despite the universal desire of the scientific space research community to increase funding for space science and applications, some observers argue that current allotments are adequate to support a vital and exciting program if appropriate policy and programmatic reforms are implemented.[8]

Space Research and the Human Spaceflight Program

The consequences of forcing science payloads better suited for independent launch by expendable vehicles onto the Space Shuttle have been widely documented. Although NASA is now procuring launch services for research payloads on expendable vehicles, because of past experiences many in the space research community remain skeptical that these vehicles will be readily available to support science payloads.[9]

Scientific accomplishment has often been cited as an important motivation for major programs (e.g., Apollo, Space Station, and the Space Exploration Initiative) that are actually space engineering and technology development programs aimed at legitimate but essentially nonscientific public purposes. Scientists argue that the science thus accomplished is often not of high priority and that support needed for more meaningful scientific opportunities is lost because policymakers believe that through these programs they are already giving adequate support to science. Many space researchers argue that both the overall space program and scientific research in space would benefit from a clarification of goals and a more formal separation of space research and human spaceflight activities. As noted above, it is now widely agreed that most science payloads should be launched with expendable vehicles and that in most cases launching replacement satellites would be preferable to having astronauts service spacecraft in Earth orbit.

The nonscientific objectives of major space program initiatives, such as the Space Station and the Space Exploration Initiative, could be fully met even if these programs were intended and designed from the beginning to pursue science objectives of the highest priority. For example, the attainment of sufficient knowledge about biological processes and human performance in space to ensure crew safety on long flights should be one of the main aims and design drivers for the Space Station. Human abilities have been, and will continue to be, important to certain scientific activities in space; for other initiatives, they are not necessary and, if present, greatly increase costs. However exciting it may be to have humans in space, they should not be subjected to the dangers of space travel unless important tasks compel their presence. Putting the emphasis on information to be returned from space—on knowledge to be gained about the Earth and other bodies or about human performance in space—simplifies the setting of priorities for both the space program and scientific space research and will eliminate the unnecessary and debilitating competition between the human space exploration program and the scientific research program.

Program Management Issues and Principles

In view of the imperatives imposed by international economic and technological competition, it is essential that the United States have an effective space research program. Managing the space research program according to several key operating principles will enhance the benefits to both science and the nation; some of these principles are already incorporated in the annual Strategic Plan of NASA's Office of Space Science and Applications (OSSA). The following list moves from general principles applicable to any research program to those more specific to scientific research in space:

• **Enhance the human resource base.** The community of working scientists and students in space research needs to be maintained and invigorated. The strength of university programs should be preserved, and there should be stable research funding to ensure vigorous basic science and a steady flow of well-educated graduates. Such funding should be aimed at basic research, development of ideas for new initiatives, and analysis and synthesis of data from space research; it should be controlled principally by the research community itself, through peer review. The components of space research performed in space are quite expensive; their associated terrestrial components are generally comparable to other fields of scientific research. Adequate investments will ensure that maximum use is obtained from data acquired from space. Finally, recognizing that students must be attracted into science and engineering at an early age, we must ensure that excellent teachers and facilities are available in both primary and secondary schools.

• **Acknowledge that choices must be made.** Science raises more intriguing questions than can be answered or even addressed. This is a sign of vitality, not difficulty. In making choices, only scientifically meritorious and technically feasible initiatives should be considered seriously. Since we cannot do everything, we need a process to select those things that will be done.

• **Capitalize on opportunities.** Special opportunities to perform good research are sometimes offered by technological developments or demands for applications. Wise investments in technological development will create such opportunities, sometimes in unexpected ways. The community should be prepared to take advantage of those opportunities that will foster scientifically meritorious research.

• **Capitalize on investments.** Having chosen to start valuable projects, we should insist on finishing them, in scientifically satisfactory and cost-effective ways. It is essential to start only the most valuable initiatives and then to understand fully all the costs of abandoning them. The cancellation of the International Solar Polar Mission and the extended stretch-out of Galileo are examples of lost investments.

• **Increase program control by principals.** Making principal investigators responsible for quality and giving scientists an increased role in program management offer potentially large benefits. As the Solar Mesospheric Mission and the first spin-stabilized scanning camera for weather satellites demonstrate, giving the scientists most directly concerned an increased role in program management offers potentially large performance advantages and reduced costs. Although this may be difficult to achieve in larger scientific efforts, the rewards are likely to justify the effort.

• **Secure access to space by diverse means.** Diverse means for access to space are necessary so that the launch vehicle or space platform can be matched to scientific objectives. Scientific missions adapted to inappropriate transportation methods are likely to be inferior.

Certain modifications in the overall space program are advisable in order to obtain maximum benefit from the available resources. For this reason, it is necessary to reexamine the fundamental assumptions and procedures governing the program. It is necessary to ascertain why costs of space research escalate exponentially with time, why costs are often much greater than originally estimated, and why it takes a decade rather than a few years to build and launch a spacecraft. Some issues that should be considered in refining the principles listed above are as follows:

• How do we take advantage of individual initiative and build resiliency, adaptability, and redundancy into the system?[10]

• Do we aim for a high probability of success with scientific missions in one try or in several tries? Will we accomplish more if we accept finite risks of failure but launch more spacecraft?

• Who should be primarily responsible for the successful performance of scientific spacecraft—NASA, contractors, or principal investigators?[11]

• How can we reduce the costs of spacecraft and launches? Should scientific initiatives be issued launch vouchers[12] that can be used to select the most appropriate and most economical means of transportation?

• What principles should govern architecture and management of data and information systems? How can they be constructed to stimulate and enhance scientific productivity?[13]

• Is the economy-of-scale argument for increasing mission size and complexity valid, both scientifically and economically?

• Are the scientific benefits of small and sharply focused scientific spacecraft sufficient to merit a high priority, especially since such initiatives can contribute in important ways to education and the strength of university programs?

The answers to these questions will govern the productivity of scientific research in space for years to come. Current policies have evolved over the history of the space program and have been shaped by the Apollo experience. Changing policies to fit the realities of the 1990s and the early 2000s may be a difficult experience for all concerned. But there is no alternative if scientific research is to flourish and if it is to be possible to accomplish even a reasonable fraction of the highest-priority scientific opportunities, however those priorities might be determined.

SCIENCE AND THE EDUCATION OF YOUNG CITIZENS

There is widespread concern about the effectiveness of primary and secondary education in preparing young Americans for their lives in an increasingly complex world. Comparative examinations reveal that American pupils lag behind those of other nations in various disciplines. Fewer college students are choosing careers in science and engineering, and only half the doctorates in science and engineering awarded by U.S. universities are being granted to U.S. citizens. The surprise of Sputnik stimulated a reexamination of the American U.S. education system. Improvements were forthcoming in the excitement generated by the Apollo program. Many look once again to the space program and to scientific research in space as possible sources of inspiration and stimulation for young citizens.

It is evident that spaceflight and human travel in space are stimulating to young people and may provide motivation to pursue scientific and mathematical subjects in the schools. Information and new knowledge derived from space research may be exciting to young minds if presented in attractive formats. The data and information systems being developed to provide interactive access to information from space research for geographically distributed researchers could also provide valuable opportunities for pupils in grade schools and high schools. Appropriate computer and software systems would allow these pupils to explore new worlds, to see the Earth from a new vantage point, and to work intellectually with new concepts and new ideas stimulated by the procession of images flowing across their computer screens. Students can perform scientific investigations, albeit simple in some cases, if they have access to actual data from space. Such efforts to provide intellectual stimulation and participation could have important long-term benefits for young people.

Space research provides a venue in which to teach the physical, chemical, and biological fundamentals that in today's standard curricula are so often presented in uninspired fashion. Some of the most important questions that space research addresses have intrinsic appeal to the nation's citizens. The origin of the universe, the nature of astronomical bodies and phenomena, the characteristics of other planets, the origins of life, and the preservation of the Earth's environment all attract public interest and could be translated into important educational opportunities for young citizens.

NATIONAL AIMS AND INTERNATIONAL COOPERATION IN SPACE

From the beginning of the space program, this nation has viewed achievements in space engineering, technology, and research as instruments of its foreign policy, believing that leadership in space activities conferred an image of national vitality and power. Certainly, the successes of Apollo in landing humans on the Moon created an aura of national prowess that was of value in the Cold War competition with the Soviet Union and overshadowed the initial image of Soviet superiority in space.

Since then, the nation's accomplishments in space science and applications and its attitudes toward space research have had important consequences. For example, the United States supports an "open skies" policy that any nation may openly and freely observe any place on Earth from space. As a corollary policy, we provide open and equal access to information derived from civil satellites. With few exceptions, other nations, including the [former] Soviet Union, have joined the United States in adhering to these policies. Similarly, it has been U.S. policy for almost a century to exchange weather information freely and openly, a process facilitated by the World Meteorological Organization (WMO). The WMO and its member countries have established standard observation times, and the U.S. weather satellites obtain temperature profiles at or near those times. The United States also participates in international scientific experiments, such as the Global Weather Experiment, with specific initiatives, including early launches and operations in space keyed to program needs. The United States has also begun a major cooperative program (Cassini) with the European Space Agency to explore Saturn and Titan.

Cooperation and collaboration in scientific research in space with international partners continue to be components of the nation's efforts to stimulate international understanding and cooperation in broader areas. Cooperative projects with the [former] Soviet Union, with European nations through the European Space Agency, and with a host of countries through bilateral agreements have produced an environment in which international cooperation is commonplace and in which nations share specific aspects of collaborative efforts.

Space Leadership and International Cooperation

The notion of maintaining "leadership in space" constitutes national policy, as reiterated in the President's statement: "A fundamental objective guiding United States space activities has been, and continues to be, space leadership."[14] However, the increasing complexity and cost of major space initiatives have stimulated a growing interest in international collaboration as a way of reducing national financial commitments to these initiatives.

Thus for the civil space program, the *National Space Policy* states, as the fourth of six objectives, the determination "to preserve the United States preeminence in critical aspects of space science, applications, technology, and manned space flight." The sixth objective is "to engage in international cooperative efforts that further United States overall space goals."[15]

However, there are obvious difficulties in seeking international partners to share costs in efforts intended to enhance U.S. preeminence. Other nations engage in, or hope to engage in, space activities for the same reasons that the United States does. For many, the emphasis on a scientific or technological specialty will be the way to seek special status through unique and unusual accomplishment. As other nations take advantage of niches in space research, it will be increasingly difficult for the United States to excel and seek preeminence across the spectrum of "critical aspects of space science." Thus new levels of international competition in space will force the United States to make difficult choices in its space research program. Some argue for selecting certain areas of space science and applications in which to excel and then concentrating talent and resources on them, in effect abandoning leadership in other areas of space research to any nations that wish to pursue them. Others argue that such choices should not be made a priori, but rather that the scientific space research program should pursue promising opportunities in space science and applications as they unfold. In either case, it will be necessary to develop a sensible process for examining alternatives and, eventually, for setting priorities among space research initiatives.

Managing International Cooperation

The scientific community and the space agencies can expect to manage an increasing number of space research initiatives conducted in collaboration with international partners. The U.S. scientific space research program already is deeply engaged in cooperative efforts at varying levels of international participation.

With operational weather satellites, nations develop and implement independent systems designed to satisfy national needs but share results on a timely basis through long-standing international agreements and networks that serve all the nations of the world. In this case, development of the international capability has been evolutionary and driven by the needs of global weather research and prediction. These cooperative arrangements provide a foundation for creating the international structure of the Earth Observing System (EOS), in which major contributions from the United States, the European Space Agency (ESA), and Japan will be combined to form a system for long-term and detailed determination of the characteristics and rates of change of the Earth system.

The International Solar-Terrestrial Physics program is similarly constructed, with independent spacecraft from Japan, the ESA, and NASA surveying distinct parts of the Earth's environment in space. Two other missions nearing launch involve international partnerships. The Ocean Topography Experiment (TOPEX/Poseidon) is a joint development with France. Cooperation with the Federal Republic of Germany and the ESA on the CRAF/Cassini mission has, in the opinion of informed observers, led to significant improvements in design and capabilities.

There are also examples in which international cooperation has not produced favorable results or has not been exploited adequately. The Omega/VIMS endeavor was an attempt to build an instrument, canceled on Mars Observer for budgetary reasons, through an international partnership, but neither cost savings nor enhanced performance capabilities were obtained. The United States, despite the technological success of Landsat, failed to appreciate the opportunities for gathering, organizing, and taking advantage of information from remote sensing. Forcing Landsat into an underfunded, quasi-commercial venture precluded cooperation with other nations and perhaps contributed to successful development of French and Soviet Earth remote sensing programs with strong ties to applications.

These and other examples suggest some guidelines that should maximize benefits to participating partners in international cooperative ventures:

- Scientific accomplishments will be enhanced if international cooperation is guided by scientific goals rather than policies mandating cooperation as a way of reducing expenses. Scientific achievements, tempered by economic reality, should be the main motivation for international cooperation.
- The joint effort should be constructed, to the extent possible, so that each partner will make a contribution that, if successful, brings independent prestige and, if not successful, does not imperil the success of the entire venture.
- The joint effort should be constructed so that responsibilities are clearly identified and the interfaces between partners, their hardware, and their data and information systems are simple, precise, and robust.

International cooperation in space research should be viewed as a means for scientific advancement, not merely as an end in itself. If correctly managed, it offers the potential for greatly enhancing accomplishment. International cooperation must be considered in selecting those space research initiatives that the nation should pursue.

INFORMATION, KNOWLEDGE, AND UNDERSTANDING

Information is a critical resource for many activities in the public and private sector alike, and managing information is now the critical task in most sophisticated activities.[16] Developed nations increasingly depend on the gathering, communication, and effective use of information.

In the United States, information-intensive industries (including banking, transportation, insurance, financial services, and professional services) accounted in 1975 for 10.2 percent of the gross national product, rising by 1985 to 12.8 percent and, according to the latest estimates, to 15 percent by 1989.[17] The production and processing of information now constitute an enterprise larger than any of the major manufacturing industries in the United States. Revenues in 1983 from the communications, computer, information, and knowledge industries together were three times those of the steel industry, twice those of the automobile industry, and nearly half as large as those of the petroleum industry.[18]

Information management is increasingly critical to space research as the number of spacecraft increases, as the improved technology of instruments provides greater resolution in space, time, and wavelength, and as the

DEFINITIONS

Data are numerical quantities or other factual representations derived from observation, experiment, or calculation.

Information is a collection of data concerning or characterizing a particular object, event, or process.

Knowledge is information organized, synthesized, or summarized to enhance comprehension, awareness, and understanding.

Understanding is the possession of a clear and complete idea of the nature, significance, or explanation of something; the power to render experience intelligible by ordering particulars under broad concepts.

program moves to the study of increasingly complex phenomena. Efficient handling of data from space and the conversion of data into information that can be shared and used by geographically dispersed investigators become an important challenge in all components of the space research program. A variety of generic issues related to the philosophy, architecture, and management of distributed and interactive data and information systems are emerging. Because of the volume of space research data, the development of computer analysis techniques based on concepts of artificial intelligence offers promise and would seem to be inevitable. Success in developing the concepts, algorithms, and technology to implement such a program will create capabilities of value to industry, both here and abroad.

As it already has for information-intensive industries and components of government, focusing on information, knowledge, and the development of understanding provides an effective organizing principle for the space program's support of scientific research in space. Interest can be expected to turn from the mechanical aspects of placing objects or humans in orbit or on other celestial bodies to the information to be gathered and exploited: the key reward will be the understanding gained. To the extent it provides the means for the conduct of scientific research in space, the governing objective of the space program will be the same as that of scientific research—namely, to achieve the maximum amount of knowledge and understanding about physical objects and processes, about their origins, about biological processes, and about human performance in space or on other planetary bodies.

Recognizing that the acquisition of data about complex systems and the conversion of this information into knowledge and understanding constitute the primary objective for scientific research in space and a major motivation for all space activities will have far-reaching, significant implications. Such an objective will

- enhance the accomplishments of space research and applications and provide an intellectual basis and support for other components of the civil space program;
- stimulate national capabilities in international economic competition;
- enhance intellectual and economic activity throughout the nation; and
- provide a focus for U.S. education that will stimulate the interest of young citizens in science and engineering and in the rapidly changing technology influencing their lives.

Moreover, such an objective will help to guide the process of contemplating and setting priorities for the space program and for scientific research in space.

NOTES

1. Bush, Vannevar. 1945. *Science—The Endless Frontier*, A Report to the President (U.S. Government Printing Office, Washington, D.C.).

2. Clarke, Peter. 1991. "Bringing Space Home to the American People," speech delivered to the Seventh Annual National Space Symposium, Colorado Springs, Colo., April 10.

3. The White House, *National Space Policy*, November 2, 1989.

4. Another frequently cited case is that of "spinoffs," or technologies and services developed as by-products of space activities. For examples, see *Spinoff* (National Aeronautics and Space Administration, 1987) and *Economic Impact and Technological Progress of NASA Research and Development Expenditures* (Midwest Research Institute, Kansas City, Missouri, 1988). Many analyses have questioned the methodology and assumptions used in the study of spinoffs, however. For example, see Office of Technology Assessment, *Research Funding as an Investment: Can We Measure the Returns?* (U.S. Government Printing Office, Washington, D.C., 1986), and references therein.

5. For example, see Stokey, Edith, and Richard Zechhauser, 1978, *A Primer for Public Policy Analysis* (W.W. Norton & Co., New York) 356 pp., and Rosen, Harvey S., 1988, *Public Finance*, Chap. 12 (Irwin, Homewood, Ill.).

6. Brooks, Harvey. 1979. "The Problem of Research Priorities," in *The Limits of Scientific Inquiry*, Gerald Holton and Robert S. Morison, eds. (W.W. Norton & Co., New York) 182 pp.

7. National Research Council. 1988. *Space Science in the Twenty-First Century—Imperatives for the Decades 1995 to 2015—Overview* (National Academy Press, Washington, D.C.) p. 2.

8. Giacconi, Riccardo. 1989. "Science and Technology Policy: Space Science Strategies for the 1990s," in *Space Policy Reconsidered*, Radford Byerly, Jr., ed. (Westview Press, Boulder, Colo., 1989) p. 84. See also Space and Earth Sciences Advisory Committee, NASA Advisory Council. 1986. *The Crisis in Space and Earth Sciences* (NASA, Washington, D.C.).

9. For previous Space Studies Board discussion on the need for expendable launch vehicles, see "The Nation's Space Program After *Challenger*: The Need for a Reassessment of the Roles of Manned and Unmanned Systems for Launching Scientific Space Missions" (an unpublished report of the Space Studies Board, May 21, 1986).

10. See the comments in Wheelon, Albert D., "Toward a New Space Policy" and in Brewer, Garry D., "Perfect Places: NASA as an Idealized Institution," both in Byerly, *Space Policy Reconsidered*, 1989.

11. See Giacconi, "Space Science Strategies," pp. 95-98 in Byerly, *Space Policy Reconsidered*, 1989.

12. For more details on this concept, see the article by Macauley, Molly K. 1989. "Launch Vouchers for Space Science Research," *Space Policy* (Nov.): 311-320.

13. For further discussion, see the following publications authored by the SSB's Committee on Data Management and Computation (CODMAC) (National Academy Press, Washington, D.C.): *Data Management and Computation, Vol. 1: Issues and Recommendations* (1982); *Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences* (1986); and *Selected Issues in Space Science Data Management and Computation* (1988). See also, Dutton, John A., 1989, "The EOS Data and Information System: Concepts for Design," *IEEE Transactions on Geoscience and Remote Sensing* 27, 109-116; and the Science Advisory Panel for EOS Data and Information, *Initial Scientific Assessment on the EOS Data and Information System*, EOS-99-1, 89-1 NASA.

14. The White House, *National Space Policy*, 1989, p. 1.

15. The White House, *National Space Policy*, 1989, pp. 2-3.

16. See, for example, Drucker, Peter. 1989. *The New Realities* (Harper & Row, New York) 275 pp.

17. Drennan, M.P. 1989. "Information Intensive Industries in Metropolitan Areas of the United States," *Environment and Planning A*, 21: 1603-1618.

18. Marchand, Donald, and Forest Horton. 1986. *Infotrends: Profiting from Your Information Resources* (John Wiley, New York) p. 31.

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The Rationale for Setting Priorities

Priorities reflect ambitions and values. Individuals or organizations set priorities to ensure that attention is concentrated on the most important objectives, to ensure that the most important things are done first. To set priorities effectively, we need to clarify our objectives. We must be confident that our purpose and operating principles advance, rather than impede, the achievement of those objectives.

Long-range priorities should facilitate management of the scientific research enterprise in a variety of ways. They should indicate directions in which the program may evolve and stimulate technological development, organizational evolution, and cooperative arrangements with other agencies and other nations. There is increasing interest in establishing priorities for federally funded research. In a study requested by the House Committee on Science, Space, and Technology, the Office of Technology Assessment cited three problems with current federal priority setting:[1]

> First, criteria used in selecting various areas of research and megaprojects are not made explicit. . . . Second, there is currently no mechanism for evaluating the total research portfolio of the Federal Government in terms of progress toward national objectives. . . . Third, although scientific merit and mission relevance must always be the chief criteria used to judge . . . , they cannot always be the *sole* criteria.

Attempts to set priorities in scientific research should concentrate on specific initiatives or proposals for activities at the margins of ongoing efforts. Just as it is impossible to say whether painting or music is the more important activity, it is impossible to rank the disciplines of science or space research in a priority order. It is essential to concentrate on the *initiatives* produced by disciplines, not the disciplines themselves.[2]

Priorities are necessary at several levels within the national scientific enterprise and within the space program and scientific research in space because science has created a wealth of opportunities for new initiatives. Some initiatives will contribute more to scientific understanding than others, some will contribute more to national economic and technological vitality, some will advance important applications of information from space, and some will assist in resolving important policy issues. Because we cannot do them all, both science and the nation need an orderly process leading to the necessary choices.

First, resources will be allocated between scientific efforts and other compelling national needs. Next, resources will be divided between basic and applied science and technological development, between scientific research in space and other ways of obtaining new knowledge. Finally, within space research itself there is competition for resources between new initiatives and maintenance of the intellectual and physical infrastructure, as well as competition among the initiatives themselves.

MOTIVATIONS FOR RECOMMENDING PRIORITIES

There are strong motivations on three levels for creating a scientific agenda through the establishment of priorities among competing endeavors:

- on the national level, to ensure that national goals are served as effectively as possible;
- for all of science, to ensure that a share of available resources commensurate with benefits is provided; and
- within science, to ensure that the most worthwhile scientific endeavors are given precedence.

There are two principal arguments in favor of acting on these motivations to achieve consensus and recommend priorities:

- **Consensus is politically compelling.** Scientists, in space research and other endeavors, believe that the benefits from science justify a share of resources adequate to pursue the most promising initiatives and to maintain the vitality of science through support for scientific education and modern scientific equipment. They also believe that public and political identification of technological initiatives as "science" may not be in the best interests of science or in the long-term national interest. Nevertheless, scientists, as individuals or in groups, have generally restricted their advocacy statements to the disciplines or initiatives in which they are most interested rather than arguing for a focused scientific agenda. But an agenda for science or for space research created and supported by the scientific community should be compelling. If scientists demonstrate that their agenda responds to national needs and to scientific imperatives, then they may argue effectively for an adequate share of resources and for an orderly progression through the suite of initiatives endorsed by the community.

• **If the players will not act, then the spectators will take the stage.**[3] Because the costs to pursue all opportunities in science or in space research exceed available resources by a large margin, choices must be made. If scientists engaged in space research cannot, or will not, set priorities among opportunities, then others whose own goals may be quite different will take the stage and make the decisions. Passivity or disarray on the part of the scientists presents the political process with the opportunity, indeed the necessity, to make choices, some of which may not be in the best interests of science. None of the reasons scientists cite for eschewing the strenuous work of reaching a consensus prevent federal officials or congressional representatives from making the necessary choices. When others act, it is the scientists who become the spectators.

COUNTER-ARGUMENTS TO THE COUNTER-ARGUMENTS

A number of arguments against recommending priorities are sometimes offered by scientists. Some of them are listed below, with explanations as to why the task group does not find them compelling.

• **There will be losers**. Indeed there will be, but there are losers now. Certainly, some who enter the priority-setting process will lose; some initiatives will necessarily be given low priority or cast aside. That happens now, sometimes for reasons unrelated to the quality of the science. It would seem preferable that scientists, as a community, help to determine the winners.

The argument over whether to set priorities is a struggle between the common good and individual goals, between enterprise and risk avoidance, and, ultimately, between good science and pedestrian endeavors. Consensus in the scientific community along with effective advocacy will, in all likelihood, produce more funds and stable funding patterns and hence strengthen science and increase the opportunities for the recommended initiatives. Some scientists, with confidence in their programs, will welcome priorities; others, with less compelling programs, will seek to delay a decision that they suspect will not be in their favor. Without a process that identifies and promotes good science and strong initiatives, resources are scattered and the strong subsidize the weak.

• **Recommending priorities is too difficult, too contentious**. Recommending priorities is difficult and can be accomplished only through a formal process in which competing initiatives are judged uniformly according to explicit criteria, preferably on the basis of written material that specifically addresses the stated criteria. The formality of the process and the existence of criteria specified in advance both tend to mitigate contention and to diminish the influence of hidden agendas. Despite the difficulty of setting priorities, all scientists do so in their own research programs. In addition, if scientists find it too difficult to create an agenda for space research, then, as argued above, others will do it for them.

• **The community will not be able to maintain consensus**. Scientists loyal to initiatives that do not receive high recommendations may tend to subvert the process, it is argued, by lobbying policymakers and Congress for special favor. Such lobbying would tend to undermine the effectiveness of the consensus. Rather than seeking to restore initiatives that have been abandoned, losers in the process would be better advised to develop more exciting initiatives. This argument and the two above combine to make a fourth:

• **Setting priorities will be counterproductive because the community will tear itself apart**. Moreover, the argument goes, at present, the rancor of losers is directed at others outside the community; if the community recommends the priorities, then that rancor will remain within the community and fester. Of course, there may be some truth to this observation. But such an outcome can be avoided by insisting on a fair, open, and formal process. Making decisions demands maturity—both the discipline to follow an agreed-upon, honest process and the courage to accept unfavorable results; to depend on the decisions of a bureaucracy is to prolong adolescence. The space research community should accept responsibility for its own future if it is to be taken seriously by others.

• **The low-priority initiatives will not be done**. Some argue that policymakers or the Congress will take advantage of any list of recommended priorities by eliminating activities with low priorities. But that is precisely the reason that priorities are recommended—in order that resources can be concentrated on the highest-priority items. The more sophisticated priority schemes, such as those discussed below, allow for balance to be achieved by allocating an appropriate fraction of resources to all essential activities. Nevertheless, if there are insufficient resources to do everything, it certainly seems preferable to abandon low-priority initiatives rather than to starve high-priority ones.

• **Scientists cannot make political judgments**. The crux of this argument is that once various disciplines put forward scientifically meritorious proposals, the decisions about relative social benefits and the extent to which the competing initiatives serve higher national purposes are beyond the purview of scientists. But the task group believes that in arguing for initiatives, scientists should be sensitive to national goals and political realities, just as politicians in considering scientific initiatives should be sensitive to scientific merit. Since scientists expect support from taxpayers, they should be willing to explain to the public why some initiatives better serve national purposes.

In a related argument, some scientists assert that only scientific merit should be considered, that other social benefits are irrelevant or only of minor concern. This argument is indeed appropriate for basic research. But meaningful initiatives, especially in space research, demand a significant fraction of national resources and thus involve opportunity costs that must be met by reducing other programs in which social benefits are of prime concern. These questions of social benefits and programmatic readiness are important to our society, and scientists must take them into account.

The fact is that scientists do make political judgments about the value of science and about their initiatives, especially when lobbying for them in agency councils and before policymakers and Congress. Some scientists also sharply criticize initiatives that are labeled as science but are approved and pursued for nonscientific motivations. Since scientists do make political judgments, it would be advantageous for them to discuss the broader values of initiatives among themselves and, in presenting their priority recommendations, to illuminate the political considerations that they found compelling.

SCHEMES FOR PRESENTING PRIORITIES

Statements of priorities, except in restricted classes of activities, cannot be unequivocal. While it is possible to rank three research missions that are candidates for new start authorization unambiguously, it is not possible to rank all activities of science or of space research in a single list. Thus any scheme for presenting priorities must be hierarchical in nature, with certain classes of activities given a higher priority than others. Moreover, priority schemes should distinguish classes of activities that actually can be compared.

Broad categories within which separate priority lists can be prepared have been proposed.[4,5] Such categories might include support for basic research and the scientific infrastructure, followed by the mandatory efforts, grand initiatives, and incremental efforts that are part of the forward march of science.[6] Such schemes can then be presented as two-dimensional matrices, with the columns representing categories and containing activities listed by relative priority. The federal Committee on Earth Sciences has presented such a priority scheme for research activities for the U.S. Global Change Research Program, specifying the relative priorities of items in the columns and of the columns themselves.[7]

In ranking initiatives or incremental activities, a number of variables and considerations must be taken into account. First, there is the scientific value to the proposing discipline and to science more generally. Other considerations include the probability of success, costs and readiness, alternate opportunities to acquire the knowledge, and benefits to society. Priority schemes must also account for unique opportunities presented by unusual events. Moreover, they must provide for balance and flexibility in the space research program. Finally, any methodology should include an analysis of the sensitivity of the rankings to variations in relative weighting of the criteria used.

Readiness is often a key issue in evaluating initiatives. For some, the requisite technology and infrastructure will exist; for others it will have to be developed. Thus readiness to do scientific research in space involves a broad range of programmatic issues, including the availability of sensors and instruments, an appropriate spacecraft and launch vehicle, adequate plans for managing data and information, and the existence of a community of scientists with the talent and commitment to ensure the success of the initiative.

High priority for a future initiative helps to develop readiness. It stimulates development of the necessary innovative technology and information management concepts and thus enhances the national technological infrastructure. High priority encourages scientists to redirect research and educational programs in ways that will contribute to the initiative.

EXPERIENCE WITH PRIORITIES IN SPACE RESEARCH

NASA's Office of Space Science and Applications (OSSA), in cooperation with advisory committees, has adopted a structured approach to the assignment of priorities within the program and among new initiatives. The current OSSA approach to developing the mission queue derives from recommendations made in *The Crisis in Space and Earth Sciences*,[8] which set forth a specific procedure for setting priorities among candidates for approval as new starts.

OSSA now produces an annual strategic plan that has two important features. First, it divides the program into five components, including ongoing efforts, major and moderate missions, small missions, utilization of the Space Station, and research-base enhancements. Second, priorities among these components are set, in effect, through a series of decision rules for allocating resources among them. The procedure for selecting new starts in each fiscal year from among a list of candidates is a formal one based on the recommendations in the *Crisis* report referred to above.

The OSSA strategic planning effort appears to be effective. The annual budget requests for new initiatives are made in the context of a formal five-year plan. Clarifying components of the program and specifically setting priorities among initiatives through creation of a five-year plan for new starts have reduced uncertainty and divisiveness in the space research community, strengthened space research, and made the program more attractive to the decision makers who provide the resources for it.

FOCUSING ON GOALS

In order to set priorities and create an agenda for science or for space research, we need to determine what is really important, both to science and to the nation. We need to assess our values and formulate clear and compelling goals.

In this context, our national goals at the highest level seem fairly clear: increase our understanding of ourselves and the world around us and contribute to national strength and the well-being of the citizens. In seeking to serve these goals through the scientific enterprise or scientific research in space, we should then consider the relative importance of more specific goals and objectives:

- Maintain the strength of the scientific enterprise.
- Concentrate on the most scientifically meritorious initiatives.
- Focus on producing information about the world around us in order to stimulate new perceptions, foster creation of knowledge, advance understanding, and enable appropriate policy action.
- Produce benefits for society, including contributions to national economic and technological vitality, the creation of national pride and sense of purpose, education and public enlightenment, and international cooperation.

Clarifying the relative importance of such goals and objectives will help us to decide what we should do. Knowing what importance others in the decision process assign to them will help create an agenda that policymakers can embrace with enthusiasm.

PRIORITIES AND THE FUNDAMENTAL ASSUMPTION

Even a program with clear priorities and a definite agenda must operate under external constraints. It will be enhanced or impeded by large-scale forces and by assumptions that may or may not be evident. Scientific research in space is clearly affected by the objectives of the civil space program, whose most basic aim has been to foster human spaceflight. This report contends that by concentrating on acquiring and processing information and converting it into knowledge and understanding, space research and the space program will advance science and contribute to national vitality. This is a fundamental assumption on which to base an agenda for national activities in space.

From the perspective of knowledge to be gained, flight to orbit and beyond is the enabling technology, not a goal in itself. In all likelihood the civil space program will eventually evolve, as has aviation, from the days in which every flight was a miracle to a multifaceted transportation system advancing a variety of human endeavors.

NOTES

1. Office of Technology Assessment. 1991. "Summary" in *Federally Funded Research: Decisions for a Decade* (U.S. Government Printing Office, Washington, D.C.) p. 139.

2. This point was made in a report by the Space and Earth Sciences Advisory Committee, *The Crisis in Space and Earth Sciences—A Time for a New Commitment* (NASA Advisory Council, 1986).

3. "[Policy] is like a play in many acts, which unfolds inevitably once the curtain is raised. To declare that the performance will not take place is an absurdity. The play will go on, either by means of the actors . . . or by means of the spectators who mount the stage." Klemens von Metternich. 1880. *Aus Metternich's Nachgelassenen Papieren* 8: 190.

4. Press, Frank, "The Dilemma of the Golden Age," address to members of the National Academy of Sciences (April, 1988).

5. Dutton, John A., and Lawson Crowe. 1988. "Setting Priorities Among Scientific Initiatives," *American Scientist* 76: 599-603.

6. Dutton and Crowe, "Setting Priorities Among Scientific Initiatives," 1988.

7. Committee on Earth Sciences. 1990. *Our Changing Planet: The FY 1991 Global Change Research Plan. Executive Summary* (U.S. Geological Survey, Reston, Va.), presented as part of the U.S. President's Fiscal Year 1991 Budget.

8. Space and Earth Sciences Advisory Committee, *The Crisis in Space and Earth Sciences—A Time for a New Commitment*, 1986.

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Conclusion

Priorities are inevitable in such human endeavors as plotting the course for a nation or disbursing or managing public funds. Implicitly or explicitly, priorities are set. We need to create an orderly agenda for scientific research in space, based on clearly defined objectives, in order to ensure that it flourishes and contributes to national vitality and the public welfare. A consensus in space research about what is truly most important will serve the best interests of both science and the nation.

Priorities reflect aspirations and values. They are derived from recognition of motivation and purpose. The governing concept of the space program was created in the early years of spaceflight. Emphasizing flight to orbit, it concentrates on expanding the domain in which humans have been present or might maintain their presence. In its most elegant form, it declares that there is a human need to explore the universe. Within this context, the Apollo mission to the Moon was the greatest success the space program has ever had, for with Apollo humans left the Earth and traveled to a distant heavenly body for the first time. But humans also need to know and understand the universe. A fundamental human imperative is not simply to explore, but to know. It is in search of knowledge and understanding that we traverse unfamiliar, often hostile, realms. The acquisition of information, the creation of knowledge, and the development of understanding are the objectives of scientific research in space and provide strong motivation and purpose for the broader space program. For, as Aristotle observed so long ago, "all men by nature desire to know." And thus a consensus about priorities and an agenda for space research focusing on the most important opportunities for new understanding will yield magnificent benefits for science and for the nation.