Science Management in the Human Exploration of Space

Committee on Human Exploration, National Research Council

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Foreword

From the dawn of the space age, human spaceflight and space science have made uneasy bedfellows. A 1960 report commissioned by Science Advisor George Kistiakowsky for President Eisenhower concluded that ". . . among the major reasons for attending the manned exploration of space are emotional compulsions and national aspirations. . . . It seems, therefore, to us at the present time that man-in-space cannot be justified on purely scientific grounds, although more thought may show that there are situations for which this is not true. On the other hand, it may be argued that much of the motivation and drive for the scientific exploration of space is derived from the dream of man's getting into space himself."[1] In addition to questions of motivation and justification, accommodating the frequently conflicting needs of human life support and scientific investigation inevitably increases pressures on finite financial and tangible resources.

The successes of joint crewed and scientific missions, from Apollo to the Hubble repair to Shuttle/MIR, show the possible benefits of cohabitation. Of course, there have also been periods of friction and consequently unrealized potential. This report of the Space Studies Board's Committee on Human Exploration examines U.S. spaceflight history and draws lessons about "best practices" for managing scientific research in conjunction with a human spaceflight program. Since NASA's current focus is the development and subsequent operation of a crewed orbital laboratory, the International Space Station, some of these lessons should be immediately useful. The report is intended to be especially germane for a national decision to resume human exploration beyond low Earth orbit.

Claude R. Canizares, *Chair*
Space Studies Board

[1]"Report of the Ad Hoc Panel on Man-in-Space," December 16, 1960, in *Exploring the Unknown, Volume I: Organizing for Exploration,* John W. Logsdon, ed., NASA SP-4407, NASA, Washington, D.C., 1995, p. 411.

Preface

In 1988 the National Academy of Sciences and the National Academy of Engineering stated in the report *Toward a New Era in Space: Realigning Policies to New Realities* that ". . . the ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on non-technical factors. It is clear, however, that if and when a program of human exploration is initiated, the U.S. research community must play a central role by providing the scientific advice necessary to help make numerous political and technical decisions."

Since its establishment in 1958, the Space Studies Board, formerly the Space Science Board, has been the principal independent advisory body on civil space research in the United States. In this capacity, the Board established the Committee on Human Exploration (CHEX) in 1989 to examine science and science policy matters concerned with the return of astronauts to the Moon and eventual voyages to Mars. The Board asked CHEX to consider three major questions:

1. What scientific knowledge is prerequisite for prolonged human space missions?
2. What scientific opportunities might derive from prolonged human space missions?
3. What basic principles should guide the management of both the prerequisite scientific research and the scientific activities that may be carried out in conjunction with human exploration?

This report addresses the third of these topics. The first was the subject of

Scientific Prerequisites for the Human Exploration of Space, published in 1993, and the second was treated in *Scientific Opportunities in the Human Exploration of Space,* published in 1994.

In developing principles to guide management of the science covered in the first two reports, the committee observed that the productivity of the scientific component of human space exploration appears to be correlated with the organizational approach and structure used to manage the program. It is reasonable, then, to look back and try to formulate principles and recommendations that can strengthen the prospects for future success. It was not the committee's charge or intent to tell NASA precisely how to organize itself; indeed, there are several possible organizational arrangements that would be consistent with the conclusions of this study. Moreover, no organizational arrangement can guarantee success in the absence of clearly articulated and commonly agreed on goals. Throughout its study, the committee has made a deliberate effort to find ways to abolish the historic dichotomy between space science and human exploration and to seek ways to encourage a synergistic partnership.

When the committee initiated its work in 1989, it appeared that NASA might proceed with a new initiative in the human exploration of the solar system, specifically human missions to the Moon and Mars, and there was an interest on the part of the Space Studies Board to influence these new activities. Since that time, urgency to proceed to an implementation phase abated as budget pressures and a drastically changed world political situation weighed against any near-term commitment. On the other hand, the nation's commitment to human presence in low Earth orbit has become firmer with the pending orbital assembly of the International Space Station. Moreover, interest in a Mars human exploration program has been aroused by the recent announcement of possible evidence of relic biological activity in a meteorite of martian origin. The associate administrators for space science and human exploration recently directed NASA field centers to initiate planning for an integrated approach that could be brought forward "sometime in the second decade of the next century." The fact that human exploration beyond low Earth orbit is once again a subject of public dialogue and active planning makes this report especially timely.

Noel W. Hinners, *Chair*
Committee on Human Exploration

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Executive Summary

Since the late 1960s, the post-Apollo future of human space exploration has been a subject of ongoing debate, incremental decisions, variable political support, ceaseless studies, and little progress or commitment toward a well-defined long-term goal. In 1989, President Bush attempted to establish a direction by announcing a long-term goal for the U.S. space program of returning humans to the Moon and then voyaging to Mars early in the 21st century. His proposal did not win political support. Indeed, implementation of human exploration of the solar system for a time virtually disappeared from public discussion, largely as a result of greatly increased federal budget pressures and the end of the Cold War, which in combination have brought about a de facto reprioritization of national goals, including an examination of the entire rationale for the U.S. civil space program.

Recently, steps have been taken to initiate integrated planning for the exploration of Mars. In parallel, the goals of the International Space Station (ISS) program include the conduct of life science research and the acquisition of practical operational experience needed to resolve issues related to long-duration human spaceflight. Concurrently, robotic exploration of the Moon and Mars is being pursued by the United States and other countries.

The Space Studies Board (SSB) constituted the Committee on Human Exploration (CHEX) in 1989 to examine the general question of the space science component of a future human exploration program. The first CHEX report, *Scientific Prerequisites for the Human Exploration of Space*,[1] addressed the question of what scientific knowledge is required to enable prolonged human space missions. The second CHEX report, *Scientific Opportunities in the Human Ex-*

ploration of Space,[2] addressed the question of what scientific opportunities might derive from prolonged human space missions.

During the development of these first two reports, it became evident to the committee that the mode of interaction between space science and human exploration has varied over the years, as evidenced by a succession of different NASA organizational structures. The committee reviewed the history of this interaction with the objective of developing a "lessons-learned" set of principles and recommendations for the future. The principles and recommendations thus evolved for managing the science component of a Moon/Mars program, whenever and however it is pursued, transcend political and administrative changes.

While this report is not intended to dictate precise organizational models, application of these principles and recommendations should facilitate a productive integration of science into a program of human exploration.

PRINCIPLES FOR SCIENCE MANAGEMENT

Three broad principles emerged from the committee's survey of past programs:

INTEGRATED SCIENCE PROGRAM—The scientific study of specific planetary bodies, such as the Moon and Mars, should be treated as an integral part of an overall solar system science program and not separated out simply because there may be concurrent interest in human exploration of those bodies. Thus, there should be a single Headquarters office responsible for conducting the scientific aspects of solar system exploration.

CLEAR PROGRAM GOALS AND PRIORITIES—A program of human spaceflight will have political, engineering, and technological goals in addition to its scientific goals. To avoid confusion and misunderstandings, the objectives of each individual component project or mission that integrates space science and human spaceflight should be clearly specified and prioritized.

JOINT SPACEFLIGHT/SCIENCE PROGRAM OFFICE—The offices responsible for human spaceflight and space science should jointly establish and staff a program office to collaboratively implement the scientific component of human exploration. As a model, that office should have responsibilities, functions, and reporting relationships similar to those that supported science in the Apollo, Skylab, and Apollo-Soyuz Test Project (ASTP) missions.

MANAGEMENT RECOMMENDATIONS

In addition to these broad principles, the committee developed a number of specific recommendations on managing space research in the context of a human exploration program. Divided into three general categories, these recommendations are as follows.

Science Prerequisites for Human Exploration (Enabling Science)

1. The program office charged with human exploration should establish the scientific and programmatic requirements needed to resolve the critical research and optimal performance issues enabling a human exploration program, such as a human mission to Mars. To define these requirements, the program office may enlist the assistance of other NASA offices, federal agencies, and the outside research community.

2. The scientific investigations required to resolve critical enabling research and optimal performance issues for a human exploration program should be selected by NASA's Headquarters science offices, or other designated agencies, using selection procedures based on broad solicitation, open and equitable competition, peer review, and adequate post-selection debriefings.

3. NASA should maintain a dedicated biomedical sciences office headed by a life scientist. This office should be given management visibility and decision-making authority commensurate with its critical role in the program. The option of having this office report directly to the NASA Administrator should be given careful consideration.

Science Enabled by Human Exploration

4. Each space research discipline should maintain a science strategy to be used as the basis for planning, prioritizing, selecting, and managing science, including that enabled by a human exploration program.

5. NASA's Headquarters science offices should select the scientific experiments enabled by a human exploration program according to established practices: community-wide opportunity announcements, open and equitable competition, and peer review.

6. The offices responsible for human exploration and for space science should jointly create a formal organizational structure for managing the enabled science component of a human exploration program.

Institutional Issues

7. Officials responsible for review of activities or protocols relating to human health and safety and planetary protection on human and robotic missions should be independent of the implementing program offices.

8. The external research community should have a leading role in defining and carrying out the scientific experiments conducted within a human exploration program.

9. A human exploration program organization must incorporate scientific personnel to assist in program planning and operations, and to serve as an interface between internal project management and the external scientific community. Such "in-house" scientists should be of a professional caliber that will enable them to compete on an equal basis with their academic colleagues for research opportunities offered by human exploration missions.

10. Working through their partnership in a joint spaceflight/science program office, the science offices should control the overall science management process, including the budgeting and disbursement of research funds.

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1

Introduction

The post-Apollo future of human space exploration beyond Earth orbit has been a subject of ongoing debate and study with little progress or commitment toward a clearly defined long-term goal since the late 1960s. In 1989, President Bush attempted to establish direction by announcing a long-term goal for the U.S. space program of returning humans to the Moon and then voyaging to Mars early in the 21st century. His proposal, termed the Space Exploration Initiative (SEI), was not followed by political action, nor has it been pursued by the current Administration. There is continued support for U.S. leadership in an International Space Station (ISS) program, however, whose utilization relates directly to a goal of long-duration human spaceflight. Indeed, the Committee on Human Exploration's first report, *Scientific Prerequisites for the Human Exploration of* Space,[1] dealt specifically with the requirements for a microgravity research facility in space.

Recently, NASA's associate administrators for space science and human exploration issued a joint directive to the Jet Propulsion Laboratory and Johnson Space Center to form a multicenter working group to fully integrate robotic and human Mars exploration planning.[2] The integrated activity is intended to result in a proposal that can be brought forward for human exploration missions that could begin "sometime in the second decade of the next century."

The committee based its second report, *Scientific Opportunities in the Human Exploration of Space*,[3] on the assumption that any program of human exploration of the solar system would have significant science content; in fact, most exploration studies[4-9] depict science goals as major motivations for such a program. The November 1996 directive cited above specifically identifies "science planning and science strategy" as a focus area for the integrated planning effort.

Although no science requirement has been identified that can be met only by a human presence, the committee believes that the scientific community should take the initiative in determining what space science goals might benefit from a human spaceflight program, given that such a program exists primarily for other reasons.

In contemplating involvement with human flight programs, many space scientists are conditioned by the fact that, despite notable successes and benefits, interactions between the scientific and human spaceflight communities have sometimes been marked by friction and dubious accommodation. Both the successes and failures constitute important lessons for any future human exploration program; while preparing its reports on the enabling (prerequisite) and enabled (opportunistic) science[10] for a human exploration program, the committee recognized the value of reviewing the history of space science programs carried out within the larger context of a human exploration program. Thus, the committee and the Space Studies Board set out to determine what attributes of past programs, particularly management attributes, might minimize the conflict and maximize the potential for a productive integration of science with human exploration.

APPROACH

The committee identified several broad principles that have contributed to mission success in the past. In doing so the committee made use of histories by John Naugle,[11] Homer Newell,[12] and William Compton,[13] as well as the recollections and judgments of committee and Space Studies Board members, many of whom played major roles in the evolution of these principles. These inputs were augmented by views solicited from representatives of the current and past space science and human exploration program offices at NASA.

To aid in identifying the effects of different management structures and approaches, the committee first reviewed the history of space science programs conducted in the context of human exploration, including the robotic program that preceded Apollo. It then analyzed those programs that involved interactions between space science and human spaceflight in terms of where mission requirements were defined and where authority for experiment selection and responsibility for funding were vested. The resulting groupings are loosely referred to as management models, although they also happen to correspond to distinct eras in the evolution of NASA's programs. The committee also considered the historical development of space biomedicine—a disciplinary area identified in its *Prerequisites* report as critical to future human exploration programs. The committee then extracted lessons learned and developed some general principles that could be applied to future programs.

MANAGEMENT OF THE CLASSICAL (ROBOTIC) SPACE SCIENCE PROGRAM

During most of NASA's existence, the Office of Space Science (OSS)[14] has formulated, funded, and executed NASA's space science program. Advised by the Space Studies Board[15] and assisted by the scientific community, OSS established long-range objectives, devised missions, selected scientists to conduct experiments, and planned the data analysis program.[16] OSS funded all robotic missions, including those conducted to gather data in support of Apollo. It budgeted for the scientific instruments, the spacecraft, and the conduct of flight operations. Prior to the advent of the Space Shuttle, OSS budgeted for and procured the expendable launch vehicles used to launch NASA's spacecraft. (In recent times, the budget for expendable launch vehicles has been restored to OSS.) OSS selected a NASA field center to manage each mission, and that center appointed a project manager and a project scientist to implement the mission.

Policies and procedures for robotic space science missions emerged during the early days of the space program from a vigorous process in which the merits of alternative procedures were debated. In many cases, procedures used to manage successful scientific projects were generalized and incorporated into formal NASA policy. The approach adopted proved fruitful, especially in planetary exploration, but also in physics and astronomy. The scientific data that came from Ranger (ultimately), Surveyor, and Apollo; from planetary programs such as Mariner, Viking, Voyager, and Magellan; from space physics missions such as the Explorers, Pioneers, and Orbiting Solar Observatories, and from astronomy programs such as the Apollo Telescope Mount (ATM) on Skylab, the Orbiting Astronomical Observatory, the International Ultraviolet Explorer, the Compton Gamma Ray Observatory, the Cosmic Background Explorer, and the Hubble Space Telescope demonstrate the effectiveness of NASA's evolved policies and practices.

A NEW ENVIRONMENT

Those who created the structure to manage science in the Apollo program had a relatively clean slate to work with, but this will not be so in the future. Officials directing a future human exploration program will have to work within, or modify, deeply ingrained policies, procedures, and cultures built up by NASA and the scientific community over 40 years. In addition, NASA has entered into a cooperative research relationship with the National Institutes of Health, for example, which could play a role in gathering the enabling biomedical data needed to support extended space missions by humans. Similarly, future human exploration missions are likely to involve significant international collaboration, as does the ISS program today. As a consequence, participants external to NASA may play an increased role in structuring or implementing the program.

A future human exploration program is not likely to be a sprint to a single, scheduled event, as was the Apollo landing on the Moon. A more probable approach is a phased one using, perhaps, the "go as you pay" strategy recommended in the report of the Augustine Committee.[17] Indeed, the November 1996 directive provides that the requested planning proposal be "credible in all respects: technically, scientifically, fiscally, with respect to risk, etc."[18]

No management arrangement can substitute for effective leadership. Such leadership will be required to identify and resolve cultural and other conflicts that will likely arise in such a large, complex, and expensive endeavor as returning humans to the Moon or traveling to Mars. The International Space Station program offers an opportunity to experiment and to begin forging a consensus on an optimal management approach. This could lead to a closer integration of the science and human exploration communities than has been achieved in the past, with a commensurate increase in both the likelihood of a human exploration program and the ultimate scientific return from it.

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12. Homer E. Newell, *Beyond the Atmosphere: Early Years of Space Science*, NASA SP-4211, NASA, Washington D.C., 1980.

13. William D. Compton, *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions*, NASA History Series, NASA SP-4214, NASA, Washington, D.C., 1989.

14. In the past, the office has been either the Office of Space Science (OSS) or the Office of Space Science and Applications (OSSA), depending on whether some or all of space applications, microgravity science, or life science were combined with space science. The report uses the OSS acronym in a general sense.

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Principles for Science Management

Based on a review of the historical interactions between human spaceflight programs and the scientific community, the committee saw its challenge as establishing a set of principles that, when employed, could facilitate the productive integration of space science into a human exploration program. These principles, along with the more specific recommendations developed in Chapter 3, might serve as a guide for decisions on what science to do in conjunction with a human exploration program, how and when to bring the scientific community into the program, and how to define the responsibilities and authorities of participating NASA offices.

There has been significant evolution in the interaction between the space science and human spaceflight communities during NASA's 40-year history. The two communities have pushed and pulled until a workable accommodation was established for each program.[1] This history can be divided into three principal eras: early lunar exploration before the Apollo landings; the Saturn launcher-based programs (Apollo, Skylab, and the Apollo-Soyuz Test Project); and the post-Saturn Space Shuttle era. Each of these eras featured a distinct but evolutionary distribution of authorities and responsibilities among the science and human spaceflight offices.

INTERACTION BETWEEN SPACE SCIENCE AND HUMAN SPACEFLIGHT COMMUNITIES

Early Lunar Exploration

The management structure used during the Ranger, Surveyor, and Lunar Orbiter programs evolved over time, culminating in the structure used to manage the very successful Lunar Orbiter program. Unlike Lunar Orbiter, the Rangers and Surveyors were not initially conceived as support missions to human flight but were reoriented to this goal as the Apollo program progressed.

After the initial Soviet space successes with the Sputnik program in late 1957, the United States attempted to gain leadership in space exploration with several hasty, ill-conceived attempts to beat the Soviets to the Moon. These robotic missions either failed totally or reached the Moon after the Soviet missions. In 1959, NASA abandoned these crash programs and formulated a systematic program to explore the Moon and the nearby planets. Two challenging lunar programs, Ranger and Surveyor, were initiated. The first NASA spacecraft to be stabilized in all three axes, the first two Rangers were designed to explore the space environment between Earth and the Moon. Surveyor originally consisted of an orbiter and a soft lander, each carrying a variety of scientific instruments.

NASA Headquarters assigned both the Ranger and Surveyor projects to the Jet Propulsion Laboratory (JPL). When measured against the existing technology and the knowledge and experience of those involved, Ranger was probably the most difficult and certainly one of the most frustrating projects ever undertaken by the Office of Space Science (OSS). Each mission carried a number of scientific instruments, each to be furnished by a scientist, most of whom worked at universities or other government laboratories. To demonstrate that the spacecraft worked, the JPL Ranger project manager wanted to launch the first Ranger as soon as possible and viewed anything that stretched the schedule as an impediment to be eliminated. The scientists, believing that their experiments were the objective of the Ranger project, found themselves in conflict with JPL and frequently with each other. The project manager also found that he could not get reliable information about the performance of the Atlas-Agena launch vehicle under development by the Department of Defense, and he did not know how many instruments he could accommodate.

When NASA assigned responsibility to JPL to conduct the lunar and planetary program, the senior management of JPL argued that they needed their own scientific advisory structure to help them plan the program. They expected NASA Headquarters to approve the JPL program, send money, and then wait for the results. Responsible for the overall program and under pressure from Congress to beat the Soviets, however, NASA Headquarters chose not to delegate responsibility for formulation of the programs to its centers: JPL could conduct studies and make recommendations, but the final decisions would be made at Headquarters. Further, NASA money would be accompanied by technical directives that JPL must follow. There were also disagreements about who would select investigators, JPL or NASA Headquarters.

The first Ranger failed in August 1961, and five more failed before Ranger 7 transmitted back more than 4,000 pictures of the lunar surface in July 1964. Rangers 8 and 9, the last two, also succeeded, and returned more than 17,000 high-quality images of the lunar surface. A major share of Ranger's problems can be traced to the struggles of a new agency whose allocation of roles and responsibilities was still being established.[2]

Surveyor suffered delays and cost overruns. Atlas-Centaur, Surveyor's launch vehicle, failed on its first launch. In mid-1962, NASA eliminated the Surveyor orbiter and all of the lander's scientific instruments except those needed to fulfill Apollo requirements. The cancellation of the Surveyor orbiter created pressure on OSS to develop an alternative lunar orbiter, because the Office of Manned Space Flight (OMSF) needed lunar photographs to select Apollo landing sites. The Space Science Board urged Congress to fund a lunar orbiter, which it did. In October 1962, in response to OMSF requirements and congressional pressure, OSS and OMSF formed a joint working group to plan a Lunar Orbiter program to map the lunar surface. Since JPL was already saturated with Ranger and Surveyor, as well as the Mariner project, this working group was asked to select a NASA center to develop the Lunar Orbiter. In early 1963, OSS started the Lunar Orbiter program at the Langley Research Center.

Surveyor 1 landed on the Moon on June 2, 1966. Two months later, on August 10, 1966, Lunar Orbiter 1 returned its first pictures of the lunar surface. Five of the seven Surveyors succeeded, and all five Lunar Orbiters successfully completed their missions.

By the time of their successful missions, the primary purpose of all three of these programs was to provide information that the Apollo project needed. In the Lunar Orbiter project, OMSF, which had overall responsibility for the Apollo program, had a customer-like relationship with OSS. That is, OMSF expressed its requirements to OSS and left it to OSS to obtain the needed data within specified time constraints. Although OSS formulated and oversaw the development and operation of all three programs and took responsibility for delays and overruns, the customer model is not an exact representation because OSS sought and maintained funding for these missions as well. After early problems, the management approach evolved to successfully support the Apollo program and enable ground-breaking lunar science.

Several observations concerning the management of space science emerged from the experience of the early days of NASA's lunar exploration program. The chances of mission success are enhanced if the objectives of each specific project or mission are clearly specified. If the prime objective of a project is to gather engineering data on a new space system, for example, and the accomplishment of scientific experiments is a secondary objective, then that fact should be made clear to the scientists participating in the project. If the prime objective of the mission is to accomplish a scientific task, then that fact must be made equally clear to the project team, which should be judged by its success in accomplishing the scientific objectives of the mission, as well as by meeting schedule and budget commitments. Also, scientific goals can be pursued most effectively if conducted within the framework of a single space science program run by one NASA

Headquarters office, and leaving selection of investigators to the Headquarters science office.

Apollo, Skylab, Apollo-Soyuz

The interactions between science and human spaceflight in Apollo, Skylab, and the Apollo-Soyuz Test Project (ASTP) were much more complicated than those in the Lunar Orbiter case. Apollo began strictly as a human spaceflight mission, as NASA's initial plans included no scientific experiments. But the Space Science Board's 1962 Iowa Summer Study examined the role for the human in research on the lunar surface,[3] and the Physics Committee, an OSS advisory group, proposed that the astronauts place optical corner reflectors on the Moon. Ultimately, a substantial lunar research program arose from these suggestions and from other experiments proposed by other NASA advisory groups.

In the early 1960s, tension arose about the conduct of lunar science on Apollo—should there continue to be one lunar science program formulated by OSS or should the Apollo project formulate and conduct its own lunar science program? How should the science program be defined and funded, and by whom?

In March 1962, an ad hoc working group on Apollo lunar science was set up at the request of OMSF.[4] The ad hoc working group met three times in early 1962 and submitted a report to the Iowa Summer Study held that summer. In the fall of 1962, the associate administrator of OSS moved to set up a more formal Joint Working Group on scientific lunar exploration and the development of scientific experiments for Apollo, structured to report to both OSS and OMSF. Discussions between OSS and OMSF continued in 1963, leading in July 1963 to a reorganization of the Joint Working Group into the Manned Space Science Division, which continued to report to the two offices (Figure 2.1). Selection and preliminary development of experiments were assigned to OSS, and development of flight hardware and integration to OMSF; each office bore the costs for its share of the experiment development.

In September 1963, OMSF established a Manned Spaceflight Experiments Board to review all experiments, whether scientific experiments proposed by OSS, technology experiments proposed by NASA's Office of Advanced Research and Technology, or military experiments proposed by the Department of Defense (Figure 2.1 shows the NASA spaceflight organization at this time, including the Manned Space Science Division). The Manned Spaceflight Experiments Board examined the technical requirements of the experiments, such as the weight, orientation, and amount of power and astronaut time required. This board did not question the scientific merits of the scientific experiments that had been approved by the associate administrator for OSS, but, in his capacity as chairman of the board, the associate administrator for OMSF retained final approval authority for all experiments that flew on the Apollo missions. Some scientists believed that

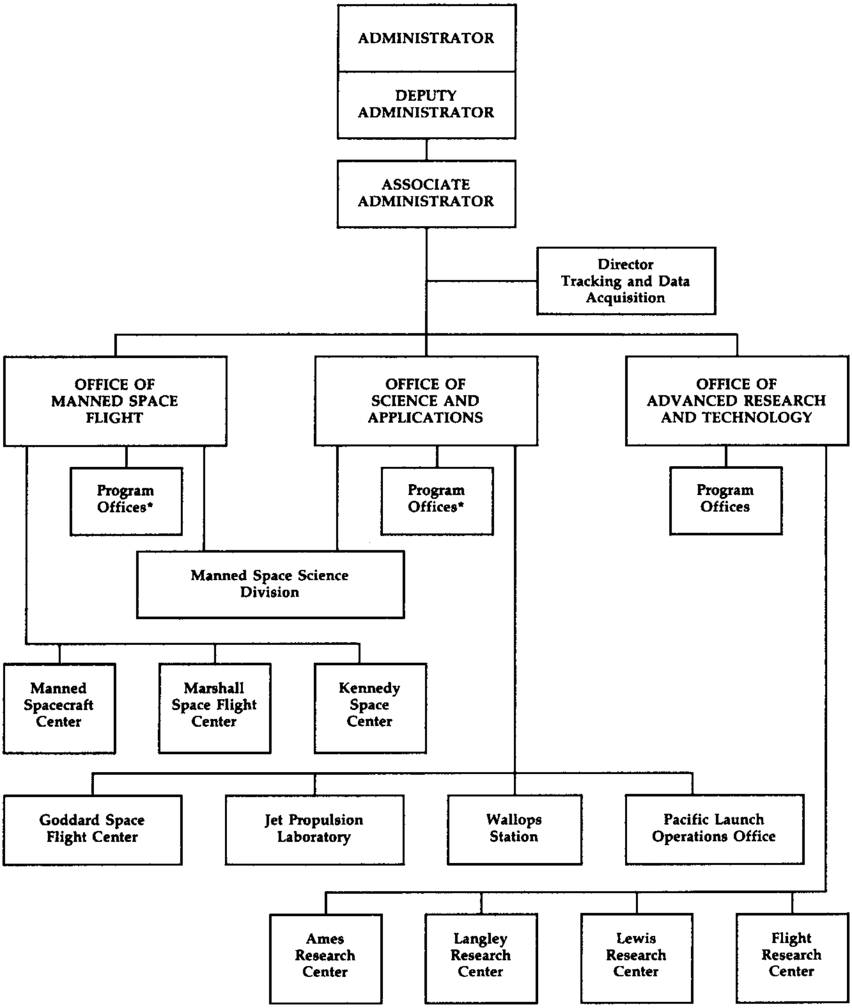

FIGURE 2.1 NASA spaceflight organization, November 1963. SOURCE: Reprinted from W.D. Compton, *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions,* NASA History Series, NASA SP-4214, NASA, Washington, D.C., 1989.

this encroached on the OSS role in science selection and constituted an unneeded administrative burden.

In September 1965, the deputy administrator of NASA issued a directive allocating responsibility for aspects of manned spaceflight programs. In part, it confirmed the existing OSS-OMSF agreement and provided that OMSF would have the responsibility of developing scientific experiments selected by OSS. It also provided that OMSF would fund the experiments. While disagreements between the staffs of OSS and OMSF did not disappear, this established the principle that there would be one space science program formulated by OSS.

This imperfect arrangement continued until September 1967, when a NASA reorganization promoted OSS head Homer Newell to NASA Associate Administrator and made Newell's former deputy, Edgar Cortright, deputy associate administrator of OMSF. Under Newell's oversight, OSS and OMSF shortly thereafter created a joint Apollo Lunar Exploration Office to be staffed jointly by OMSF and OSS and to be physically and organizationally located in the OMSF Apollo Program Office (Figure 2.2). A former OSS manager of the highly successful Lunar Orbiter program was designated the new director of lunar exploration. Reporting to him were four assistant directors, all experienced OSS program managers and program scientists. For administrative matters, hardware development, and funding status, the director of lunar exploration reported to the director of the Apollo program office, but for all scientific matters he reported to the associate administrator for OSS. Thus, the Lunar Exploration Office was established not as a liaison office or working group, but rather as an integral component of the Apollo program organization within OMSF, charged with responsibility for lunar experiment hardware that would both meet the Apollo schedule and satisfy OSS science requirements.

The arrangement proved successful, based on several important factors. Cortright, now deputy associate administrator of OMSF, knew and trusted the OSS people in the Lunar Exploration Office and hence could assure the director of the Apollo program office that they would accomplish the tasks assigned to them. At the same time, because the leaders of the office were all experienced OSS employees, they enjoyed the confidence and support of the associate administrator of OSS and knew that when they had completed their work for the Apollo program they would return to OSS. Key to success were the shared recognition by OSS and OMSF of the need for a joint office and staffing of this office with experienced individuals of acknowledged achievement.

Having proved its worth during the Apollo missions, the joint project office concept was also applied to the Apollo Telescope Mount (ATM), the solar observatory operated by the astronauts on the Skylab space station (1973-1974). OSS had already selected experiments for the Advanced Orbiting Solar Observatory (AOSO) prior to approval of Skylab. Forced to cancel AOSO because of a shortage of funds, OSS transferred the instruments to the ATM. The ATM project manager reported jointly to the associate administrator for OSS and the associate administrator for OMSF, just as in the case of Apollo.

For the 1975 Apollo-Soyuz Test Project (ASTP), the associate administrator for OSS was given the responsibility for selecting the experiments to be performed during the mission. After a false start resulting from a desire to expedite

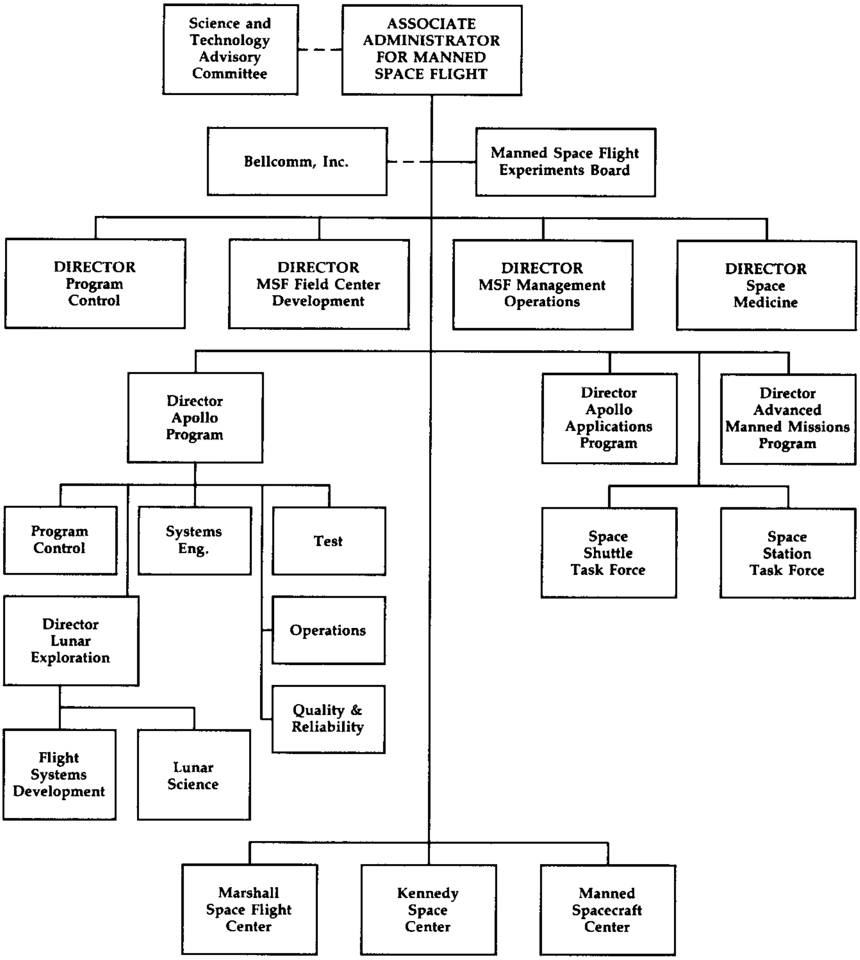

FIGURE 2.2 Office of Manned Space Flight organization, 1969. SOURCE: Reprinted from W.D. Compton, *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions*, NASA History Series, NASA SP-4214, NASA, Washington, D.C., 1989.

selections, OSS assembled science working groups that successfully carried out a standard, if greatly accelerated, competitive selection process in just two months.

Several lessons were learned from Apollo, Skylab, and ASTP about the conduct of scientific research during human spaceflight. The formation of a joint program office, staffed by representatives of both NASA's science and human spaceflight offices, was shown to be an effective solution to the day-to-day tensions that arose between advocates of human exploration and advocates of science concerning the scientific experiments conducted during the Apollo missions. In addition, unifying Apollo and ASTP science objectives and processes with ongoing science management processes of OSS avoided duplication of activities, provided more effective cross-fertilization among scientific disciplines, and minimized confusion among policymakers. In one sense, however, the Apollo management approach reversed the earlier Lunar Orbiter approach: in Apollo, funds were sought and obtained for the science program by OMSF rather than by OSS, even though OSS selected the investigations to be carried out.

Shuttle/Spacelab

The relationship between the science and human spaceflight offices shifted again in the Space Shuttle/Spacelab program.

After the completion of the Apollo Moon landings, lack of support for an expensive space program in the Administration and Congress closed the Saturn-Apollo production lines and led NASA to propose a new, low-cost launch vehicle, the reusable Shuttle, for transporting humans to and from Earth orbit. In 1969-1970, NASA hoped to develop the Shuttle and a space station in parallel. Financial guidelines imposed on NASA by the Administration, however, precluded simultaneous development of two major human spaceflight systems. In 1971, when the members of NASA's Space Station Task Force found that the station had been postponed indefinitely, they abandoned work on it and, instead, turned to a pressurized, habitable container that the Shuttle could carry to and from orbit. Spacelab resulted from the work of the task force as a substitute for a continuously orbiting space station. In January 1972, the President approved the Shuttle program. In December 1972, the European Space Research Organization undertook to develop and manufacture Spacelab.[5]

There were disagreements within NASA and within the scientific community itself over the value of Shuttle/Spacelab. Scientists from disciplines that required long-duration observations or collection of data from orbits beyond those achievable by the Shuttle argued that a switch by NASA to the Shuttle/Spacelab system would leave them unable to conduct their research. Astronomers who had been disappointed by the loss of the first Orbiting Astronomical Observatory, on the other hand, were concerned about a national commitment to the Large Space Telescope (ultimately the Hubble Space Telescope) without a provision for the ability to repair any malfunctions.

Within NASA, the associate administrator of OSS organized and co-chaired the Shuttle Payload Planning Steering Group. This group, made up of members of OSS and OMSF, worked to make sure that OMSF, which was developing the Shuttle, understood space science requirements and that OSS understood the capabilities and constraints of the Shuttle. Out of these discussions emerged agreement on the need for upper stages for the Shuttle to place some scientific missions in higher orbits and a commitment by NASA that the Shuttle would be designed so that it would be able to launch and service the Hubble telescope, and that the Hubble telescope, in turn, would be able to be launched and serviced by the Shuttle.

After establishing the scientific requirements, the associate administrator for OSS controlled all space science and life science payload activity during development and operation of the Spacelab. The associate administrator for OSS funded and managed their development, rather than have them funded by OMSF and managed by a joint OSS/OMSF Spacelab Program Office as was done in Apollo and Skylab. The NASA administrator directed the associate administrator for OSS to select the scientists (the "payload specialists") who would fly on the Shuttle and conduct experiments in the Spacelab. The associate administrator for OSS would also direct the activities of the Spacelab Payload Project at the Marshall Space Flight Center and select the final payload complement.

This arrangement was nearly the opposite of that used for Lunar Orbiter. In the latter, the office responsible for human spaceflight set requirements for the science office for the data it needed to land humans on the Moon. In the case of the Shuttle/Spacelab program, the science office established "requirements" for the human spaceflight office to optimize the platform for science utilization. In reality, the fundamental characteristics of the Shuttle system were fixed by a complex network of budgetary, technological, and national security constraints, rather than being defined by scientific users. The resulting Shuttle capabilities were presented to the scientific community as an "opportunity" that could be adapted to a certain extent and exploited, for example by the Spacelab (and later Spacehab and other systems).

During development, testing, and operation of Spacelab, OSS continued to control the payload activity. When Spacelab became operational, OSS continued to fund and manage the development of all space and life science payloads. OSS selected not only the scientific investigators, but also the scientists who flew as payload specialists in the Shuttle to conduct experiments.

In spite of very high costs, greater than expected complexity, and initial skepticism of the science community, Shuttle/Spacelab has been successful in that some high-quality laboratory science has been accomplished. In addition, the Shuttle has been successfully used to repair and service the Solar Maximum Mission and the Hubble Space Telescope, as well as subsequently to upgrade the scientific capabilities of the Hubble. Several lessons were learned from experience with this program. First, science carried out within the context of human spaceflight needs the involvement of scientists at all stages of the program's conceptualization, development, and operation. This continuing involvement is necessary to ensure that realistic science goals are established that take advantage of human presence, and that missions, flight hardware, and procedures are designed to promote the accomplishment of science. In addition, the Spacelab program again confirmed the practice of the investigators being chosen by the science office rather than the program office responsible for flying the mission. In the Shuttle/Spacelab era, OSS budgeted for and managed science funding, similar to the earlier Lunar Orbiter but in contrast to Apollo. On the other hand, the Shuttle/Spacelab program reversed the customer relationship of Lunar Orbiter in the sense that OSS expressed accommodation requirements to OMSF, rather than OMSF tasking OSS with its data needs.

MANAGEMENT PRINCIPLES

In summary, a structure that grew out of the debate during the formulation of the Ranger and Surveyor programs was successfully used for the Lunar Orbiter program of robotic spacecraft that provided data used to select landing sites for the Apollo crews. During the early lunar exploration era, the office responsible for human spaceflight set requirements for the space science office in the sense that they told the science office what information they needed and when they needed it. The science office was given the management and budgetary authority to obtain needed data as it saw fit, albeit within a strict schedule. A more elaborate structure evolved during the Apollo program, and subsequently the Skylab and ASTP programs, to explicitly manage the interaction between the space science and human spaceflight programs. During this era, a joint management team that included representatives of the science office and the spaceflight office oversaw the conduct of space science within the context of the larger exploration programs. A third structure evolved during the era of the Spacelab program of pressurized modules and unpressurized pallets flown in the cargo bay of the Shuttle. During this period, the team approach that proved so successful during Apollo was largely abandoned, and the earlier model whereby the spaceflight office set requirements for the science office was essentially reversed, with the science office developing and negotiating requirements for orbital platforms to be designed, built, and launched by the spaceflight office.

The direction of the "customer-provider" relationship, and the related issue of which party advocates and obtains the science funding, are important because of their impact on project implementation. This in turn bears on the importance of clear priorities and the organizational locus of science decision making.

The committee identified three broad principles in its survey of the history of the interaction between space science and human spaceflight. Experience with the Ranger and Apollo programs demonstrates that waste and duplicated effort are minimized, and clear lines of authority are delineated, if the scientific aspects of solar system exploration are the responsibility of a single Headquarters office. Thus, the first principle is the following:

INTEGRATED SCIENCE PROGRAM—The scientific study of specific planetary bodies, such as the Moon and Mars, should be treated as an integral part of an overall solar system science program and not separated out simply because there *may be concurrent interest in human exploration of those bodies. Thus, there should be a single Headquarters office responsible for conducting the scientific aspects of solar system exploration.*

A common problem in programs with multiple goals is the relationship between actual and perceived priority of those goals. This issue has arisen to varying degrees in almost all of NASA's human-related space projects. Human exploration is not undertaken primarily for scientific reasons, but it has important scientific elements.[6] Thus it is essential that the relative priority of all the competing goals be well understood by all participants. Accordingly, the second broad principle is that clear objectives and priorities should be established at the level of individual component flight projects in the program in order to properly integrate science goals with the nonscience goals of human exploration:

CLEAR PROGRAM GOALS AND PRIORITIES—A program of human spaceflight will have political, engineering, and technological goals in addition to its scientific goals. To avoid confusion and misunderstandings, the objectives of each individual component project or mission that integrates space science and human spaceflight should be clearly specified and prioritized.

Although a human exploration program cannot be justified by scientific considerations alone, such missions have the potential, as noted in the committee's second report,[7] to provide significant scientific opportunities. NASA's experience indicates that the scientific return can be enhanced if there are good communications and a cooperative working relationship between engineering implementers and the scientists. A demonstrated means of facilitating productive integration of space science and human spaceflight is to establish a joint office. Thus, a third broad principle is that space science conducted in the context of a human exploration program should be managed through a joint spaceflight and science program office:

JOINT SPACEFLIGHT/SCIENCE PROGRAM OFFICE—The offices responsible for human spaceflight and space science should jointly establish and staff a program office to collaboratively implement the scientific component of human exploration. As a model, that office should have responsibilities, functions, and reporting relationships similar to those that supported science in the Apollo, Skylab, and Apollo-Soyuz Test Project (ASTP) missions.

Chapter 3 considers these principles and their implications in further detail in the context of the committee's two earlier reports.

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3. Space Science Board, *A Review of Space Research: The Report of the Summer Study Conducted Under the Auspices of the Space Science Board of the National Academy of Sciences at the State University of Iowa*, Iowa City, Iowa, June 17-Aug. 10, 1962, Publication 1079, National Academy of Sciences, Washington, D.C., 1962.

4. Details of the evolution of the relationship between science and the Apollo program are provided in *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions*, by William D. Compton (NASA History Series, NASA SP-4214, NASA, Washington, D.C., 1989); see also *Beyond the Atmosphere: Early Years of Space Science*, by Homer E. Newell (NASA History Series, NASA SP-4211, 1980).

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6. Space Studies Board, National Research Council, *Scientific Prerequisites for the Human Exploration of Space*, National Academy Press, Washington, D.C., 1993.

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3

Management Recommendations

In its first (*Prerequisites*) report,[1] the committee designated the research required to undertake and optimize human exploration as "enabling science." In addition to enabling science, there is scientific research that can be conducted or significantly facilitated by the existence of a human exploration program. In its second (*Opportunities*) report,[2] the committee called this "enabled science" because it is enabled by the existence of the human exploration program. There is also a third category of space science, the classical space science conducted by the Office of Space Science (OSS) that does not involve humans working in space. This third category of science is straightforwardly managed according to well-established OSS policies and procedures similar to standard practices of the non-NASA research community, without the national policy issues and complicating effects of human presence.[3]

SCIENCE PREREQUISITES FOR HUMAN EXPLORATION (ENABLING SCIENCE)

The central issue in enabling science for a human exploration program concerns the collection and analysis of the prerequisite life science and biomedical data required in order to determine whether long-duration human spaceflight, such as that required for a voyage to Mars, is advisable or even possible. The committee's *Prerequisites* report identified two broad categories of enabling science required for undertaking human exploration of the inner solar system.

"Critical research issues" are those where present-day ignorance is great enough to pose unacceptably high risks to human spaceflight beyond low Earth orbit. These issues have the highest probability of being life-threatening or seriously debilitating to space explorers[4] —that is, they are in effect potential "show-stoppers" for a human exploration mission.

A second category, "optimal performance issues," includes those that do not appear to be seriously detrimental to the health and well-being of humans in space, but that could degrade the performance of humans in flight or on extraterrestrial surfaces. Some of the issues in this category could later be found to be critical, especially in the areas of long-duration extraterrestrial habitation or return to terrestrial gravity following extended flight. In addition, some optimal performance issues relate to the enhancement of scientific yield.

Continued pursuit of enabling science research is required to determine whether human exploration of the solar system is, in fact, feasible. Much research related to the necessary objectives is already under way in various parts of NASA's organization.

Establishing Requirements for Enabling Science

The program office responsible for carrying out a human exploration program should be responsible for establishing the mission-critical enabling requirements. Program life scientists should be tasked with generating specific, goal-oriented questions to address anticipated problems in, for example, human physiology, psychology, and radiation protection. The program office cannot, however, be expected to possess the expertise necessary to fully develop all of the requirements alone, and experts without previous experience with NASA life science programs might contribute untapped expertise to the critical problems posed by long-duration human spaceflight. Program officials should call on other elements of NASA, for example, the office(s) responsible for the various space sciences, as well as non-NASA entities, such as the National Institutes of Health and the Department of Energy, for specialized assistance. Exploration program research goals should also be brought to the attention of recognized experts in the relevant disciplines within the academic community.

Thus, the committee recommends that:

1. The program office charged with human exploration should establish the scientific and programmatic requirements needed to resolve the critical research and optimal performance issues enabling a human exploration program, such as a human mission to Mars. To define these requirements, the program office may enlist the assistance of other NASA offices, federal agencies, and the outside research community.

Selection of Enabling Science Investigations

Once goal-oriented questions have been defined, the talents of the very best scientists and engineers will be necessary to obtain and analyze the data needed to satisfy these requirements. The U.S. civil space science program has achieved its many successes in creating new knowledge by developing, early in the space era, and continuing to refine a comprehensive, broadly based, widely understood and accepted investigator selection process based on peer review. Fundamental characteristics of this process have been described in several Space Studies Board reports.[5,6] The committee recommends that:

2. The scientific investigations required to resolve critical enabling research and optimal performance issues for a human exploration program should be selected by NASA's Headquarters science offices, or other designated agencies, using selection procedures based on broad solicitation, open and equitable competition, peer review, and adequate post-selection debriefings.[7]

The best medical scientists should participate in and review the enabling biomedical research programs.

Management of Space Biomedical Sciences

In carrying out Recommendation 2, it must be recognized that several factors complicate biomedical sciences in NASA. At times in the past, NASA management and the astronaut corps have perceived biomedical scientists as overly cautious. Early in the space program, for example, physicians responsible for the safety of humans in space argued for more data and more animal flights. This position conflicted with that of the managers of human spaceflight activities and the astronauts, who were anxious to orbit a man before the Soviets and were willing to accept greater risks.

More generally, NASA has had trouble engaging the interest of the highest-caliber biomedical scientists to conduct space-related research because the frontiers of biomedicine have been in terrestrial laboratories, rather than in space. Although over its three decades space biomedicine has had some significant spinoffs that have contributed to terrestrial medicine, such as the telemetering of data and miniaturization of equipment, the unique microgravity environment of space has not attracted the attention of the majority of researchers studying the physiology or diseases of Earth-bound humans. Even in discipline areas with particular promise for space-based research, the administrative and engineering complexity and long time scales of space experimentation tend to discourage investigators immersed in the broader world of fast-paced biological research. The main rationale for space-related biomedical research, then, has been the postulate that humans will spend extended periods in the space environment and explore the solar system.

In this context, many biomedical scientists have maintained that biomedical science should reside in a separate office with its own associate administrator (a life scientist).[8] The space biomedical sciences programs were maintained under the direction of the Office of Space Science (OSS) until late 1970 when NASA Headquarters decided that the only life science research, other than exobiology, that should be continued was research related to the safety of astronauts during lengthy spaceflights. OSS phased out its bioscience program, and the Office of Manned Space Flight (OMSF) was assigned responsibility for the remaining life science program. Skylab became the only facility for life science research, and the associate administrator of the OMSF selected the life science experiments conducted there. This arrangement prevailed from 1971 through 1975. In 1975, with Skylab completed, no human flights scheduled until the late 1970s, and no long-duration human flights scheduled for the foreseeable future beyond that, control of the total life science program was transferred back to OSS, where it remained until 1993.

When biomedical research was a component of OMSF there was a perceived inherent conflict of interest between purely scientific dictates and the imperative to get on with spaceflight. When incorporated into OSS, on the other hand, biomedical sciences tended to have lower priority relative to the traditional space physical sciences. Nonetheless, for most of NASA's history, its administrator, after examining the arguments, has rejected the notion of a separate office. Thus, until recently, space biomedicine has always been a subcomponent of either OSS or OMSF.

In 1993, the life sciences other than exobiology and studies related to the origin of life were transferred to the new Office of Life and Microgravity Sciences and Applications (OLMSA). Although it did not lead to a totally separate biomedical life sciences office, the policy of uniting the space biomedicine and microgravity sciences in one office recognized their broad similarities as experimental rather than observational sciences, and their similar infrastructure requirements as laboratory-oriented research disciplines. Advantages of this unification, which include strengthened management focus, have been compared with disadvantages in the Space Studies Board report *Managing the Space Sciences*.[9]

As a result of a sweeping policy-level review, which evaluated NASA's management structure in the context of a customer service model, NASA Administrator Daniel Goldin subsequently aggregated the agency's functional offices into "strategic enterprises." Initially, OLMSA, which has responsibility for space biomedicine, was grouped with the physical space sciences in the Scientific Research Enterprise. Later, OLMSA was relocated out of this enterprise, and joined with the Office of Space Flight (OSF) in the Human Exploration and Development of Space (HEDS) strategic enterprise.[10] Superficially, this configuration resembles the former management arrangement whereby the life sciences were included within a NASA program office whose main interest and responsibility were the conduct of spaceflight. But within HEDS, OLMSA's charter is defined as leadership in "space biological, physical, and chemical research and aerospace medicine, supporting technology development, and applications using the attributes of the space environment."[11] In addition, OLMSA's Research and Analysis (R&A) and flight programs are managed by customary peer-review practices to achieve broad scientific goals laid out in widely circulated solicitations.

In 1996, however, budgetary control over the scientific components of the space station program, including the NASA-Mir Research Program and Space Station Facilities and Utilization, was removed from OLMSA and placed under the management of the International Space Station program within OSF, OLMSA's partner in the HEDS strategic enterprise. In this arrangement, these important elements of the space laboratory research program are effectively once again vested in NASA's human spaceflight office, at least from a budgetary point of view, where they are directly subordinated to the priorities of the flight program.[12]

As argued in the Space Studies Board reports cited above (including the 1970 report), a program of extended-duration human spaceflight will place major new demands on the life sciences. In order to overcome past management problems, to bring additional high-quality research and researchers into the program, to ensure that those scientists are able to conduct cutting-edge research, and to enable NASA management to incorporate human biomedical factors directly into programmatic decisions at the highest levels, the committee recommends that:

3. NASA should maintain a dedicated biomedical sciences office headed by a life scientist. This office should be given management visibility and decision-making authority commensurate with its critical role in the program. The option of having this office report directly to the NASA Administrator should be given careful consideration.

SCIENCE ENABLED BY HUMAN EXPLORATION

Early examinations of enabled science in human exploration included the Space Science Board's Iowa Summer Study[13] on the scientific opportunities arising from the Apollo program, and the work of NASA's Task Force on the Scientific Uses of a Space Station.[14] In its *Opportunities* report, the present committee discussed the distinction between enabling and enabled science in human exploration. If these research categories are clearly distinguished and the distinction maintained during the course of implementation, then the most problematic issue that remains is the relative role of humans and robots. The tension between advocates of human exploration and advocates of robotic science missions has existed for a long time. Some researchers are convinced that space science objectives can be met using Earth-controlled or autonomous robotic spacecraft alone. Others believe, equally firmly, that the future viability of the entire U.S. civil space program depends on human presence in space. If these differences are carried into the future, the committee believes that the only result will be the diminution of the total U.S. space effort, probably at a significant cost to both groups.[15]

Humankind is still in the earliest phases of the exploration of the inner solar system. Further evolution can be expected in the concepts and details of a continuing program and in possibilities for enabled scientific research. Enabled science should be competitively evaluated in terms of its relationship to other space science initiatives and opportunities. Such an evaluation would involve not only scientific quality but also programmatic issues such as cost, schedule, and the value added by human presence. Cost is a particularly difficult issue to address. It is often argued that the incremental cost of individual science investigations is low in comparison to the total cost in human flight programs, and that such investigations therefore should be incorporated into the human flight mission. In the past, this rationale, combined with a flight opportunity, has been used to justify the flight of experiments whose merit was questionable or at least not clearly established by peer review. A pernicious side effect of this reasoning can be the imposition on the program or flight system of research requirements, together with their attendant costs and risks, that are unwarranted by the quality of the potential science return.

At the same time, there will arise occasions where it is decided, after thorough evaluation, that an investigation of high scientific merit should be accomplished within the human exploration program even though some programmatic considerations, such as cost, might argue for implementation through a purely robotic program. A past example illustrates this point: the Apollo Telescope Mount on Skylab successfully accomplished scientific objectives derived from planning for the robotic Advanced Orbiting Solar Observatory, a program that had been canceled in the space science program for budgetary reasons.

Space Science Strategies and Science Goals and Priorities

A key element in the conduct of space science has been the development of a research strategy for each major scientific discipline.[16] These strategies are developed, to the extent possible, without regard to the mode of implementation and evolve as knowledge, technology, and instrumentation advance. The strategies are crafted in such a way as to leave technical implementation to the agency programmatic planning process since the scientific committees that develop them are not constituted to have the information and expertise necessary to address implementation options in detail. Another reason that the research strategies avoid implementation recommendations is that they are intended to remain valid for 5 to 10 years, while the programmatic context changes on a much shorter time scale due to dynamics of annual budgets and overall national policy.

Each discipline's science strategy is used by NASA to help establish priorities for missions supporting that discipline. Because these priorities should apply also to research enabled by human exploration of the inner solar system, the committee recommends that:

4. Each space research discipline should maintain a science strategy to be used as the basis for planning, prioritizing, selecting, and managing science, including that enabled by a human exploration program.

Selection of Enabled Science Investigations

The overall merit of enabled space science is of central importance. Thus the decision-making process leading to the selection of a given enabled science project can only be articulated and defended by rigorous and systematic evaluation. Such tools already exist in the form of the practices and procedures used to select NASA's science programs.[17] In addition, there are good reasons for locating control of the selection process at NASA Headquarters.[18] As in the case of enabling science (Recommendation 2, above), rather than develop new procedures, the committee recommends that:

5. NASA's Headquarters science offices should select the scientific experiments enabled by a human exploration program according to established practices: community-wide opportunity announcements, open and equitable competition, and peer review.

Implementation of Enabled Science

Once science investigations are selected for a human exploration program, their actual implementation in the context of a specific set of mission constraints, e.g., mass, volume, and power requirements, necessarily involves interactions between the science offices and those charged with implementing the flight program. Taking note of the broad success of the procedures devised for this purpose during the Apollo, Skylab, and Apollo-Soyuz programs (see Chapter 2), the committee recommends that:

6. The offices responsible for human exploration and for space science should jointly create a formal organizational structure for managing the enabled science component of a human exploration program.

INSTITUTIONAL ISSUES

Protocol Review

In its first report, the committee commented that the potential hazards to be faced by the crews on human exploration missions beyond Earth orbit "must be adequately addressed within the context of a comprehensive program of health and safety. To do otherwise imposes unacceptable risks on the entire human exploration enterprise."[19] Experience from previous NASA programs, however, shows that concerns about astronaut health and safety, or about the forward and backward contamination of planetary bodies (planetary protection), can conflict with, or impede accomplishment of, the objectives of a specific mission. Analysis of the history of planetary quarantine during the Apollo era, for example, exposes a series of organizational and implementation problems, ranging from unclear allocation of authority and responsibility to deficient integration of engineering requirements and personnel training into the program.[20] One study concluded, after examining alternatives, with a preference that "a life science program office would be established within NASA with responsibilities for life science research and for protecting against extraterrestrial contamination, both outbound and inbound. As recommended in the 1960 NASA report, this program would carry status equivalent to that of other program offices within NASA."[21] Experience illustrates a clear need for independent objective review of the handling of these concerns and of constituent protocols by individuals and offices *not* responsible for the conduct of the flight program. The committee recommends that:

7. Officials responsible for review of activities or protocols relating to human health and safety and planetary protection on human and robotic missions should be independent of the implementing program offices.

The Role of Universities

Since its earliest days, the space program has benefited from the involvement of academic scientists in the development of science priorities, mission concepts, and instruments for spacecraft, and analysis of results. NASA needs the ideas, skills, and support of the academic community. This participation provides a steady source of new talent and rapid dissemination of results of the space program into the scientific and engineering communities.[22] In the early days of NASA, as competition for room on satellites increased, NASA established a formal procedure to ensure equitable access to its missions by all scientists whether at universities, NASA field centers, or other federal and commercial laboratories.[23] The human exploration of space will extend over a long period and thus will require a continual input of new talent. In addition, the program will generate new knowledge and technology. Therefore, the committee recommends that:

8. The external research community should have a leading role in defining and carrying out the scientific experiments conducted within a human exploration program.

This recommendation is consistent with an earlier Board recommendation that NASA's research be conducted out-of-house wherever possible.[24]

The Role of Scientific Expertise Within the Program

In the early days of NASA, many academic scientists and NASA engineers thought that scientific research should be conducted by academic scientists and that the function of NASA field centers should be to provide launch vehicles, spacecraft, and engineering help to these academics. It rapidly became apparent to both groups, however, that each NASA field center responsible for a NASA scientific mission, including the contractor-operated Jet Propulsion Laboratory, needed a group of highly qualified space scientists to help on a day-to-day basis with conceiving new missions, developing approved missions, and providing a channel of communication between the center and the academic community. The best way to guarantee and monitor the competence of these in-house scientists is to expect them to compete successfully with their academic colleagues for the opportunity to participate in the NASA space science program as investigators themselves.

In response to downsizing pressures and an agency desire to preserve and enhance the vitality of its science programs, the role of government space scientists, especially those at NASA field centers, has recently been reexamined in a number of Board studies and reports.[25-27] An alternate approach to the vital functions performed by these scientists that is structured around external, but tightly coupled, "science institutes" has been examined recently by NASA.[28] While not directed at a human exploration program, these analyses' rationale and conclusions apply directly to such a program, adapted perhaps to NASA's organizational configuration at such a time. The key point is that the functions currently exercised by NASA in-house project scientists are essential ones that should be maintained in any alternative organizational arrangement that might be adopted.

Consistent with findings of these studies, the committee makes the general recommendation that:

9. A human exploration program organization must incorporate scientific personnel to assist in program planning and operations, and to serve as an interface between internal project management and the external scientific community. Such "in-house" scientists should be of a professional caliber that will enable them to compete on an equal basis with their academic colleagues for research opportunities offered by human exploration missions.

Funding for Science in a Program of Human Exploration

The question of the programmatic source of funding for scientific experiments was considered at length by the committee. It can be argued that to attain the desired control over the science part of the program, the science office should budget for the science and control the science budget allocation and accountability process. A counter-argument holds that the expense of conducting science in conjunction with human spaceflight is so high that it should be budgeted under the human spaceflight program, where it would be a comparatively small cost element, to prevent it from crowding out other science priorities in science office budgets.

Historically, as Chapter 2 recounts, both of these approaches have been used at different times. During the early lunar exploration program, the Office of Space Science budgeted for the robotic missions. In contrast, the Apollo, Skylab, and Apollo-Soyuz programs themselves budgeted for their associated science. During Shuttle/Spacelab, the science programs have budgeted for science experiments and data analysis, although the Shuttle program has funded most of the integration of the payloads into the Shuttle and much of the common support equipment.

The committee concluded that there has been no clear correlation between science effectiveness and the programmatic source of science funding; rather, the committee's deliberations revealed that science effectiveness is correlated with the control of the management processes by which the science is selected and implemented. Science budgeting responsibility, on the other hand, has historically been largely a function of expediency and opportunity. For example, the high national priority of the Apollo program supported the high cost of Apollo science. In the Shuttle era, the assignment of science budgeting to the science office was driven by the desire to minimize the apparent cost of the Shuttle program.

It was pointed out to the committee that the synchronization of budgeting by the science office (or offices) in support of science enabled by a human exploration program remains a problem. That is, if the science office assumed the responsibility for budgeting human exploration program science, it would be required to ask for funds to plan and support science for human flight programs not yet approved in order for the science to be incorporated into the program in its early phases. This additional science funding could prove difficult to attract under these circumstances, and the science office would naturally be cautious about committing any of its existing resources specifically to such support. At the same time, NASA would like to be able to offer any scientific advantages of a human exploration program as part of its advocacy for that program. The committee appreciates the problem and suggests that the best approach is implied by Recommendation 4, that is, that strategic science planning that avoids prescribing implementation details can constitute a sound basis for preparation, negotiation, and participation, and offers the best assurance of appropriate balance and optimum synergy between robotic and human exploration. This approach would use the science strategies to inform a continuing dialogue and integration with the human exploration enterprise, strengthening both efforts and helping forestall late and ineffective science involvement.

In a zero-growth or declining budget environment, such as exists now and which also existed as Apollo tailed off, one cannot pretend that the higher cost of doing business within human spaceflight programs has no impact on science programs (see, for example, note 12 below). Thus, while scientific accomplishment does not appear to have been strongly correlated with the source of funding in the past, control of the science budgets by the science offices may, in fact, be essential to maintain the quality of the research program and a productive balance with flight system development in the future. The committee's general principle favoring the establishment of a joint spaceflight/science program office provides a mechanism for this within the context of a sound management structure; the committee therefore recommends that:

10. Working through their partnership in a joint spaceflight/science program office, the science offices should control the overall science management process, including the budgeting and disbursement of research funds.

NOTES AND REFERENCES

1. Space Studies Board, National Research Council, *Scientific Prerequisites for the Human Exploration of Space*, National Academy Press, Washington, D.C., 1993, pp. 10-12.
2. Space Studies Board, National Research Council, *Scientific Opportunities in the Human Exploration of Space*, National Academy Press, Washington, D.C., 1994, pp. 6-7.
3. Office of Technology Assessment, *NASA's Office of Space Science and Applications: Process, Priorities, and Goals*, U.S. Government Printing Office, Washington, D.C., January 1992.
4. Space Studies Board, National Research Council, *Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies*, National Academy Press, Washington, D.C., 1996.
5. Space Studies Board, letter report to NASA Associate Administrator Harry Holloway from Louis J. Lanzerotti and Fred W. Turek, April 26, 1993.
6. Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995; Recommendations 5-1 through 5-8, pp. 57-58.
7. These considerations have most recently been addressed by the Board in connection with the Explorer mission line. See the report *Assessment of Recent Changes in the Explorer Program*, Space Studies Board, National Research Council, National Academy Press, Washington, D.C., 1996.
8. These views can be traced back to early days of the human flight program. See, for example, the Space Science Board's *Life Sciences in Space*, National Academy of Sciences, Washington, D.C., 1970, p. 19.
9. Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995, p. 37.
10. National Aeronautics and Space Administration, *NASA Strategic Plan, February 1995*, NASA, Washington, D.C.
11. National Aeronautics and Space Administration, *Budget Estimates—Fiscal Year 1998*, p. SAT 2-3, 1997. Scientific objectives are also prominent in the four top-level HEDS goals presented in *NASA's Enterprise for the Human Exploration and Development of Space—The Strategic Plan, January 1996*, NASA, Washington, D.C.
12. This is clearly indicated by supporting narrative in NASA's FY98 *Budget Estimates* volume: "This past year NASA consolidated the management of Space Station research and technology, science utilization, and payload development with the Space Station development and operations program in order to enhance the integrated management of the total content of the annual $2.1 billion budget. The Space Station program manager is now responsible for the cost, schedule, and technical

performance of the total program. The OLMSA and OMTPE [Office of Mission to Planet Earth] remain responsible for establishing the research requirements to be accommodated on the space station and will respond to the direction of the program manager to ensure the utilization priorities and requirements are consistent with the overall Space Station objectives." (p. HSF 1-2)

13. Space Science Board, National Research Council, *A Review of Space Research: The Report of the Summer Study Conducted Under the Auspices of the Space Science Board of the National Academy of Sciences at the State University of Iowa, Iowa City*, Iowa, June 17-Aug. 10, 1962, Publication 1079, National Academy of Sciences, Washington, D.C., 1962.

14. Task Force on the Scientific Uses of Space Station, *Space Station Summer Study Report—March 1985*, NASA, Washington, D.C., March 21, 1985.

15. The relationship between human and robotic exploration is discussed at greater length on pp. 9-15 in the Space Studies Board report, *Scientific Opportunities in the Human Exploration of Space.*

16. See, for example, Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, and Space Studies Board, National Research Council, *Strategy for Space Biology and Medical Science for the 1980s and 1990s*, National Academy Press, Washington, D.C., 1987.

17. The Space Studies Board addressed aspects of NASA research selection procedures in several letter reports: letter to Associate Administrator Harry Holloway on April 26, 1993 (*Space Studies Board Annual Report*—1993, p. 32); letter to Life Science Division Director Joan Vernikos on July 26, 1995 (*Space Studies Board Annual Report*—1995, p. 85).

18. Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995, pp. 57-58.

19. Space Studies Board, National Research Council, *Scientific Prerequisites for the Human Exploration of Space*, National Academy Press, Washington, D.C., 1993, p. 12.

20. These problems are briefly referred to in the Space Studies Board report *Mars Sample Return—Issues and Recommendations*, National Academy Press, Washington, D.C., 1997, p. 35. A detailed account of the Apollo quarantine program experience is provided in *Back Contamination: Lessons Learned During the Apollo Lunar Quarantine Program*, by John R. Bagby, Jr., July 1, 1975 (prepared for the Jet Propulsion Laboratory under Contract #560226).

21. T. Mahoney, *Organizational Strategies for the Protection Against Back Contamination*, NASA-CR-149274, Final Report, University of Minnesota, St. Paul, Minn., 1976, pp. 39 and 47. This recommendation provides a sample organization chart that shows an Office of Life Science reporting, in parallel with the Office of Space Science and the Office of Manned Space Flight (and several others), directly to an Associate Administrator for Programs. The "1960 NASA report" cited in the quotation was the report of the NASA Bioscience Advisory Committee, dated January 25, 1960. In his report (cited in note 19 above), J. Bagby concluded that "[m]anagement of any future quarantine operation should be established as a special program office out of the office of the Administrator of NASA" (p. 42, emphasis in the original).

22. Homer E. Newell, *Beyond the Atmosphere: Early Years of Space Science*, NASA History Series, NASA SP-4211, NASA, Washington, D.C., 1980, pp. 223-241.

23. John E. Naugle, *First Among Equals: The Selection of NASA Space Science Experiments*, NASA History Series, NASA SP-4215, NASA, Washington, D.C., 1991, pp. 79-196.

24. Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995, pp. 43-44.

25. Space Studies Board, letter to NASA Chief Scientist France A. Cordova from Claude R. Canizares, March 29, 1995, *Space Studies Board Annual Report—1995*, p. 74.

26. Space Studies Board, letter to NASA Chief Scientist France A. Cordova from Claude A. Canizares, August 11, 1995, *Space Studies Board Annual Report—1995*, p. 88.

27. Space Studies Board, National Research Council, *Managing the Space Sciences*, National Academy Press, Washington, D.C., 1995.

28. National Aeronautics and Space Administration, *NASA Science Institutes Plan*, NASA, Washington, D.C., 1996.

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