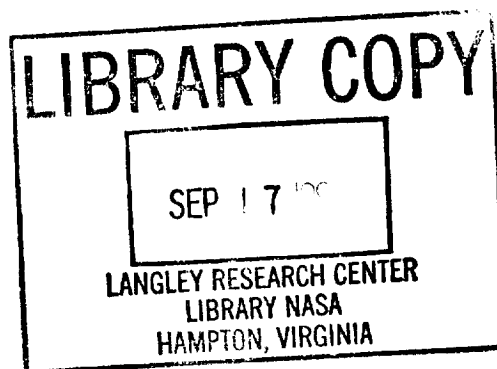


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Scientific Assessment of NASA's Solar System Exploration Roadmap

**Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council**



August 23, 1996

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NATIONAL RESEARCH COUNCIL
COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS
2101 Constitution Avenue Washington, D.C. 20418

SPACE STUDIES BOARD

Office Location:
Milton Harris Building
Room 584
2001 Wisconsin Avenue, N.W.
(202) 334-3477
Fax: (202) 334-3701

August 23, 1996

Dr. Jurgen H. Rahe
Science Program Director
Solar System Exploration
Mail Code S
National Aeronautics and Space Administration
Washington, DC 20546

Dear Dr. Rahe:

In your letter of March 26, 1996, you requested that the Committee on Planetary and Lunar Exploration (COMPLEX) assess NASA's Solar System Exploration Roadmap¹ and report on the degree to which the Roadmap is responsive to the scientific priorities outlined in past National Research Council (NRC) reports. COMPLEX understands that you need this assessment by September 1, 1996, because the Roadmap is an integral part of a new solar system exploration strategic plan to be developed by NASA this fall.

As you requested, the assessment was conducted at COMPLEX's June 24-28, 1996, meeting held at the National Academies' Arnold and Mabel Beckman Center. The assessment was based on material sent to committee members for review prior to the meeting, extensive briefings by Dr. Larry Soderblom of the Roadmap development team, and subsequent discussions in executive session throughout the week of the meeting.

COMPLEX finds the goals and objectives set forth in the Roadmap to be generally consistent with the recommendations and priorities contained in past NRC reports, including *An Integrated Strategy for the Planetary Sciences: 1995-2010*,² *The Search for Life's Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution*,³ and *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980s*.⁴ Moreover, the fact that the Roadmap was developed jointly by scientists and technologists is a strength consistent with recommendations in the 1995 NRC report *Managing the Space Sciences*.⁵

COMPLEX's general assessment of the Roadmap is that it outlines a rich and ambitious program of planetary exploration through the year 2012. In particular, COMPLEX commends the Roadmap development team for adopting an approach to planetary exploration advocated by the *Integrated Strategy*, that is, systematically addressing key physical and chemical processes rather than taking the more traditional approach of cataloging and classifying planetary bodies.

It is, however, important for the Roadmap's scientific objectives to be brought into sharper focus with some indication of priorities for study and critical measurements to be made. Although COMPLEX recognizes that NASA committees will be charged with identifying priority mission sets, it notes that the Roadmap, in its current form, provides no obvious framework within which such priorities can be set. COMPLEX also notes that the *Integrated Strategy's* highest priorities for solar system exploration, i.e., intensive studies of comets, Mars, and the Jupiter system, are not singled out for special attention, although all are, admittedly, included in the Roadmap.

Three other specific issues that COMPLEX wishes to raise here concern the quests related to human destiny and life's origins and the issue of nonflight programs. The human destiny quest is disconnected from the actual proposed campaigns and their scientific objectives. The connection should be clearly stated in the Roadmap report. The quest regarding life's origins is recognized as a high priority in previous NRC studies,^{6,7} but it is essential that the Roadmap's stated expectations for fulfilling the quest not be exaggerated. This part of the Roadmap report should be carefully assessed to ensure that it rests on realistic statements. COMPLEX also notes that the Roadmap does not recognize the role of nonflight programs. Although their exclusion may have been a consequence of the Roadmap development team's charter, it is clear that laboratory experiments, modeling, Earth- and space-based telescopic observations, and field studies are essential to an understanding of the solar system, as documented in NRC reports.^{8,9,10}

Despite these shortcomings and other criticisms outlined in the accompanying Assessment, the program of planetary exploration described in the Roadmap has both significant potential for scientific discovery and the prospect of wide public appeal. The Space Studies Board and COMPLEX recognize that the Roadmap is an evolving document and that modifications will be made in response to changing circumstances and new developments (e.g., the recent announcement of the possible discovery of microfossils in a martian meteorite). Accordingly, we offer our services to you should you wish a review of a later draft of the Roadmap. In addition, the SSB and COMPLEX, in particular, look forward to the implementation of the Roadmap and will be pleased to review this phase of the solar system exploration program at an appropriate time.

Sincerely,



Claude Canizares
Chair
Space Studies Board



Ronald Greeley
Chair
COMPLEX

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SCIENTIFIC ASSESSMENT OF NASA'S SOLAR SYSTEM EXPLORATION ROADMAP

At its June 24-28, 1996, meeting, the Space Studies Board's Committee on Planetary and Lunar Exploration (COMPLEX), chaired by Ronald Greeley of Arizona State University, conducted an assessment of NASA's *Mission to the Solar System Roadmap* report.¹ This assessment was made at the specific request of Dr. Jurgen Rahe, NASA's science program director for solar system exploration.

The assessment includes consideration of the process by which the Roadmap was developed, comparison of the goals and objectives of the Roadmap with published National Research Council (NRC) recommendations, and suggestions for improving the Roadmap.

ELEMENTS OF THE ROADMAP

The Roadmap concept is a new element in NASA's strategic planning process. It is defined in the letter requesting this assessment as "a visionary but affordable outline of mission and technology development necessary to complete the overall survey of planetary bodies and to undertake the next evolutionary step of extensive in situ exploration and sample return from accessible bodies." In the briefings COMPLEX received, it was emphasized that a key element of the Roadmap is the close coupling of scientific objectives for the exploration of the solar system with the technology development needed to meet those objectives.

The report of the Roadmap development team identifies three major goals, or "quests," for solar system exploration. Quest one is to chart human destiny in the solar system. Quest two is to seek the origin of life and its existence beyond Earth. Quest three is to explain the formation and evolution of the solar system and of Earth within it.

These quests would, according to the Roadmap, be addressed through five focused scientific themes, or "campaigns." Each campaign contributes to the pursuit of one or more quests. For example, the campaign on the study of the evolution of Earthlike environments is relevant to the quests concerning both the origin of life and the formation and evolution of solar system objects.

Although the Roadmap does not outline specific missions to implement the campaigns, it does include illustrative or "portrait" missions and the technologies enabling them. The intention of the Roadmap is to demonstrate that solar system exploration is a rich program with high scientific potential, wide public appeal, and opportunities for enhancing science education at all levels.

Since specific mission sets are not defined and the costs of the portrait missions are not given, COMPLEX cannot comment on the affordability of the Roadmap. COMPLEX's impression is that implementation of the programs outlined in the current Roadmap will far exceed the resources likely to be available for solar system exploration in the near future, and thus COMPLEX believes that priorities must be set.

THE PROCESS OF DEVELOPING THE ROADMAP

COMPLEX was told that the Roadmap was the result of some 6 months of deliberations between some 50 planetary scientists and more than 50 engineers, technologists, and educators. Representatives from relevant advisory bodies, including the chairs of various NASA science working groups, participated in the development of the Roadmap to ensure that input from previous and ongoing studies related to solar system exploration was not overlooked. Additional input was received at a workshop open to the entire planetary science community.

COMPLEX's overall assessment of the process by which the Roadmap was developed is that it was fair and creditably reflects the calibre of its authors. This evaluation is based not only on the committee's examination of the Roadmap report and the briefings received at the June meeting, but also on the first-hand experiences of COMPLEX's chair as an observer at meetings of the Roadmap development team. The large development team and resulting diversity of opinions no doubt contributed to COMPLEX's overall impression that the Roadmap tries too hard to satisfy everyone.

ASSESSMENT OF THE ROADMAP'S QUESTS

In this section, COMPLEX comments on the Roadmap's three quests and how they relate to priorities and recommendations contained in relevant NRC reports.

Quest: Chart Human Destiny in the Solar System

Implicit in this quest is the assumption that humans will eventually leave Earth and explore the solar system. If that is correct, then this quest is fundamental to planetary exploration. Moreover, the validity of this quest has been acknowledged in reports by both COMPLEX² and the SSB's Committee on Human Exploration (CHEX).³ The latter report, in particular, contains an extensive discussion of the role of scientists in human space exploration missions.

As presented in the Roadmap, the human destiny quest does not appear to be geared primarily toward science, but rather toward the future of human space exploration. Yet, the related campaigns address scientific objectives. Thus, the link between this quest and the campaigns as described in the Roadmap should be strengthened. The relationship between the future habitability of Earth and possible hazards from impacts, in particular, should be explicitly addressed in the relevant campaigns.

Quest: Seek the Origin of Life and Its Existence Beyond Earth

The search for life's origins is given high priority in various NRC reports.^{4,5,6} The solar system affords numerous opportunities for studying biogenic processes, whether or not life actually exists, or has ever existed, on bodies other than Earth. Targets identified as high priorities in the Roadmap include the chemistry of Titan's atmosphere, the hypothesized "ocean" beneath Europa's surface ice, cometary dust, and rocks and soil returned from Mars. These are in accord with previous NRC recommendations.⁷ This quest's emphasis on characterizing environments that have or have ever had water is appropriate.

A weakness in this quest is the absence of any mention of laboratory studies of candidate early life processes. This aspect, emphasized in past NRC reports,⁸ includes the study of the origin and evolution of metabolism, replication, and RNA catalysis. If the search

for life and associated chemistry on other planetary bodies is conducted without regard to these and other relevant processes, it is possible that critical evidence for life will be overlooked.

Despite the potential for each single sample of Mars to provide compelling evidence about martian life, some aspects of this quest should be carefully supplemented if NASA is to lay the foundations for a more robust, long-term study of life beyond Earth. While searching for a fossil record on Mars may be a high priority, the possible discovery of microfossils on Mars must be linked to other evidence of life. In other words, the search for a fossil record on Mars should be tightly coupled with a search for more generic evidence of past life, such as the detection of chemical indicators or anomalous isotopic fractionations of carbon and sulfur.

The general search for life's origins is an important activity, and the Roadmap is correct in singling it out as a priority undertaking. However, the search must be undertaken in a realistic manner and with regard to current exobiological thinking.⁹ Ill-conceived and unrealistic priorities will only compromise the project in the long run.

Quest: Explain the Formation and Evolution of the Solar System and Earth Within It

The goal of understanding the formation and evolution of the solar system is fundamental to space science, as documented in numerous NRC reports.^{10,11} The campaigns to meet this quest provide focus for understanding many of the key aspects of how planets operate as complex physical and chemical systems, which is a high priority identified by COMPLEX.¹² However, a flaw is the possible perception that this quest will be finished at the end of the period of time covered by the Roadmap, when, in fact, many questions will remain (and new questions will be raised) even if the Roadmap is fully implemented.

ASSESSMENT OF THE CAMPAIGNS

In this section COMPLEX assesses the various campaigns by which the Roadmap proposes that the three quests will be addressed.

Campaign: Building Blocks and Our Chemical Origins

This campaign seeks to inventory the physical, chemical, and isotopic properties of materials that formed the solar system, to understand how these materials have evolved into the early planets, and to identify accessible resources for exploitation during human exploration missions. In general, the campaign is in keeping with COMPLEX's past recommendations and priorities.¹³

Although the Roadmap identifies several key technologies necessary for outer solar system exploration, it should make a stronger tie between scientific studies of near-Earth objects and the human exploration of space. Moreover, the Roadmap does not appear to reflect the importance of interplanetary dust particles (or interstellar grains) for addressing such factors as planetary origins and formation of regolith, as has been suggested previously.¹⁴

Campaign: Prebiotic Chemistry in the Outer Solar System

This campaign focuses on the satellites Europa and Titan and their potential as natural laboratories to understand how diverse environments can lead to the origin of life. Studies of prebiotic organic chemical evolution on these bodies is consistent with NRC recommendations.^{15,16} This campaign provides opportunities to study prebiotic organic chemical evolution on a planetary scale in order to develop models of active regions in which chemical evolution could have occurred.

Although results from this campaign could have wide public appeal, caution is dictated in two areas. First, the Roadmap strongly ties this activity to anticipated results from *Galileo* (for Europa) and *Cassini* (for Titan), and this dependence is accentuated by the decision to omit the study of other potential locations of prebiotic chemical evolution. Triton, in particular, would be a reasonable additional target to include in the future.¹⁷ Second, the campaign may promise too much about the potential for these satellites to tell us anything about life. Even if an understanding of prebiotic organic chemical evolution on a planetary scale is obtained from studies of bodies in the outer solar system, caution must be used in applying the results to Earth.

COMPLEX has an additional concern about the use of the word "biological" to describe the "natural" laboratories on these moons or in the name of portrait missions (e.g., the Titan Biological Explorer). This usage is not justified and may prove to be a severe misdirection. It should be made clear that, for the present, Europa and Titan will serve as *chemical* rather than biological laboratories.

Campaign: Evolution of Earthlike Environments

This campaign focuses on the classic problem of understanding the evolution of the surfaces and atmospheres of the triad of terrestrial planets—Venus, Earth, and Mars. Its particular emphasis is on understanding how Mars and Venus have evolved so differently from Earth after presumably experiencing similar origins in the solar nebula. The role of water is central to this campaign, especially in the case of Mars, given its importance for the possible development of life and as a resource for human exploration missions.

This campaign's emphasis on the study of Mars's climate, and the possibility that it is or was an abode of life, is consistent with COMPLEX's previously published priorities.¹⁸ The further exploration of Venus has, however, not been given as high a priority by COMPLEX.

COMPLEX has attached very high priority to a better understanding of martian atmospheric circulation^{19,20} as the key component of the climate system and for comparative studies of atmospheric dynamics. Yet, this Roadmap campaign does not effectively address this key objective for Mars.

Campaign: Formation and Dynamics of Earthlike Planets

This campaign focuses on the internal dynamics of terrestrial planets. As such it is complementary to the campaign "Evolution of Earthlike Environments" (see above) and is consistent with COMPLEX's recommendations.²¹

The interaction of the atmosphere and hydrosphere with the surface and interior of Earth plays a crucial role in our planet's evolution. The role of water in these interactions is, undoubtedly, key to explaining why our planet is the only terrestrial body with plate tectonics. Consequently, it is difficult to discuss the dynamics of the solid Earth without taking this interaction into account.

This campaign identifies all the inner planets, together with the Moon and Io, as pertinent objects to study. If the focus on Earthlike planets is to be adopted, then Europa should probably be added to the list because it is a rocky object with a volatile-rich surface and it has been geologically active in the recent past. Although COMPLEX has discussed the operation of planets from a broader perspective²² and has included essentially all planetary bodies, the Roadmap places relatively little emphasis on the workings of the interiors and surfaces of non-Earthlike planets. Important processes not identified in the Roadmap include mantle convection, which probably occurs in the interiors of icy and rocky satellites of the outer planets, and the dynamo action responsible for the outer planets' magnetic fields.²³ Because an understanding of the processes occurring in Earth benefits greatly from seeing how these same processes operate under different conditions, it would be a mistake to confine the study of these processes only to Earthlike planets as the Roadmap does.

At the time of this assessment, this campaign's "Goals and Expected Achievements" had not been articulated in the Roadmap, and so this critical aspect could not be reviewed by COMPLEX.

Campaign: Astrophysical Analogs in the Solar System

This campaign is essentially a study of basic physical and chemical processes occurring in planetary systems. Its objectives emphasize the fundamental processes that led to the formation and evolution of the solar system, yet the proposed execution of this campaign is a series of portrait missions focusing almost exclusively on the giant planets. Consequently, the campaign title is misleading. Of the portrait missions identified in the Roadmap, the outer planet missions are highly responsive to the priorities set by COMPLEX.²⁴ The scientific objectives address key questions about atmospheric dynamics, chemical and isotopic composition, magnetospheric structure, and auroral phenomena, but the objectives neglect physical processes in the interiors of the giant planets. While the portrait mission to Mercury is a poor match to this campaign on the giant planets, such a mission is a previously identified priority of the space-physics community.²⁵

SUMMARY

The Roadmap provides a potentially exciting and scientifically rewarding program of solar system exploration that is generally consistent with recommendations made in NRC reports. The Roadmap is responsive to COMPLEX's existing advice except as follows:

1. The scientific objectives in the Roadmap need to be brought into sharper focus with some indication of priorities for study and critical measurements to be made. Although it recognizes that NASA committees will be charged with identifying priority mission sets, COMPLEX notes that the Roadmap, in its current form, provides no obvious framework within which such priorities can be set. It also notes that COMPLEX's highest priorities²⁶ for solar system exploration, i.e., comets, Mars, and the Jupiter system, are not singled out for special attention, although all are included in the Roadmap.
2. The Roadmap contains scientifically rewarding and potentially newsworthy exobiology investigations in several campaigns. Care must be taken by NASA not to exaggerate the benefits of specific missions to the search for life. To do so will undercut the significance of the science that can be achieved in missions to Europa and Mars and may damage the credibility of NASA's missions with exobiological goals.

3. The titles of two of the Roadmap's campaigns should be modified to reflect their true content. "Astrophysical Analogs in the Solar System" is a misleading label for what is essentially a study of the physical and chemical processes in the giant planets. Perhaps a better title for this campaign is "Planetary Processes in Natural Laboratories." The campaign dealing with the formation and dynamics of Earthlike planets should include "history" in its title.
4. Various Earth-based investigations are essential to an understanding of the solar system. Laboratory experiments, modeling, Earth-based telescopic observations, and field study are excluded from the Roadmap but must be recognized as essential elements²⁷ in solar system studies.
5. The role of humans and the scientific goals in the human destiny quest should be identified and tied to the campaigns. Recent NRC reports (e.g., *Scientific Opportunities in the Human Exploration of Space*²⁸) clearly outline the role and should be recognized in the Roadmap.
6. The joint development of the Roadmap by scientists and technologists is a strength. However, there are some technological inconsistencies in the current version that need to be rectified. For example, the exploration of the Jupiter system emphasizes the use of radioisotope thermoelectric generators, whereas other missions to the outer planets focus on advanced solar cells and deployable solar concentrators. Another technology issue handled in an anomalous manner is communications. The Roadmap outlines various means for improving communication systems in spacecraft but pays no attention to the potential benefits obtained by improvements to the existing Deep Space Network.

In conclusion, COMPLEX is generally positive about NASA's Solar System Exploration Roadmap and commends the development team for synthesizing the study during today's rapidly evolving budgetary and policy environment.

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SHMUEL WINOGRAD, IBM T.J. Watson Research Center
CHARLES A. ZRAKET, The MITRE Corporation (retired)

NORMAN METZGER, Executive Director

