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Space Studies Board
Commission on Physical Sciences, Mathematics and Applications

April 21, 2000

Dr. Carl Pilcher
Science Program Director
Solar System Exploration
Code S
National Aeronautics and Space Administration
Washington, DC 20546

Dear Dr. Pilcher:

In your letter of January 18, 2000, you reiterated a verbal request made in November 1999 for the views of the Space Studies Board's (SSB's) Committee on Planetary and Lunar Exploration (COMPLEX) on a number of issues concerning the Science and Mission Roadmap[1] recently prepared as part of the Solar System Exploration science theme's contribution to strategic-planning activities conducted by NASA's Office of Space Science. In particular, you asked that COMPLEX provide you with the following:

- Perspectives on the degree to which the Roadmap addresses the priorities outlined in past COMPLEX reports; and
- Recommendations for strengthening the scientific rationale and mission priorities contained in the Roadmap.

COMPLEX understands that you need this assessment because the Roadmap, an integral part of the Office of Space Science's new strategic plan, is currently undergoing revision prior to publication.

Work on this assessment began at COMPLEX's November 1-5, 1999, meeting at the

[1] Solar System Exploration Subcommittee, *Exploration of the Solar System—Science and Mission Strategy*, Jet Propulsion Laboratory, Pasadena, California, December 1999.

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Arnold and Mable Beckman Center in Irvine, California, and was conducted in parallel with the preparation of the committee's input to an SSB-wide assessment of the strategic plan resulting from the Office of Space Science's Strategic Planning Workshop held in Galveston, Texas, in November 1999. Subsequent to your November 1 presentation of the Roadmap, COMPLEX received additional perspectives from committee member Wendy Calvin and SSB director Joseph Alexander based on their role as observers at the Roadmap presentations held in Galveston on November 2.

In the course of this study COMPLEX reviewed two drafts of the Roadmap: the November 1999 and December 1999 drafts distributed to the committee prior to the November 1999 meeting and in January 2000, respectively. Although in the context of another activity, COMPLEX also was briefed on the technical and programmatic aspects of one of the new missions featured in the Roadmap, the Venus Surface Sample Return. In addition, the committee reviewed relevant reports issued by COMPLEX and other National Research Council (NRC) committees (e.g., *The Search for Life's Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution* [1990], *An Integrated Strategy for the Planetary Sciences: 1995-2010* [1994], *The Role of Small Missions in Planetary and Lunar Exploration* [1995], *Review of NASA's Planned Mars Program* [1996], "Scientific Assessment of NASA's Solar System Exploration Roadmap" [1996], *Exploring the Trans-Neptunian Solar System* [1998], *The Exploration of Near-Earth Objects* [1998], and *A Science Strategy for the Exploration of Europa* [1999]) and held extensive discussions in closed session.

COMPLEX's assessment of the program outlined in the Roadmap is mixed. The committee is generally positive about many of the near- and mid-term flight missions and related activities highlighted in the Roadmap because they address priorities outlined in the committee's past reports (see attached Assessment for full details). COMPLEX is particularly pleased to see that NASA continues to place a high priority on Mars exploration and that a new initiative relating to Mars sample handling and analysis is proposed. Similarly, COMPLEX is pleased that prominent attention is given to a comet nucleus sample-return mission. Moreover, the committee commends NASA for formulating a program of planetary exploration that attempts to systematically address key physical and chemical processes rather than merely cataloging and classifying planetary environments. Finally, the Roadmap appears to strike an appropriate balance between the broad thematic goals of understanding origins and understanding planets advocated in COMPLEX's *Integrated Strategy*.[2]

These positives aside, COMPLEX has a number of serious concerns about particular aspects of the Roadmap and the program of solar system exploration it advocates. These concerns are, in approximate order of priority, as follows:

- The Roadmap does not clearly indicate the scientific objectives of solar system exploration and the critical measurements that must be made to meet these objectives, nor does it describe how existing or proposed missions will make these measurements. These problems stem in large part from the Roadmap's emphasis on the three broadly scoped "Quests" and are compounded by the document's lack of a coherent structure, a consistent format, a cohesive

[2] Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, pages 33-34.

introduction, and a comprehensive supporting text.

- The scientific justification for both existing and proposed mission lines is not adequately presented.
- The scheduling of, and the rationale for, several of the proposed missions (e.g., Europa Lander, Titan Explorer, and Saturn Ring Observer) relative to the flight programs they logically build on (e.g., Europa Orbiter and Cassini/Huygens) need to be clarified.
- The Roadmap includes no information concerning the process by which it was assembled, the identity of the authoring group, or the means by which the recommended mission sequences were prioritized.
- The scientific rationale for the selection of the Venus Surface Sample Return mission is unclear.
- Many of the major missions in the proposed "To Build a Planet" mission line either are not identified as high priorities in existing COMPLEX reports or might more properly be justified in other programmatic contexts.
- The handling of non-mission activities, such as R&A programs and education and public outreach, does not adequately indicate the importance of these activities.
- Important linkages between the Solar System Exploration, Astronomical Search for Origins, and Sun-Earth Connection science themes and Astrobiology either go unmentioned or are obscured.
- The asymmetry in the discussion of how the goals of Solar System Exploration relate to the Astronomical Search for Origins and the Sun-Earth Connection science themes, on the one hand, and to Astrobiology, on the other, might be taken to imply that the latter has a special status.
- Any detailed discussion of technological issues has been excluded.

In its 1996 assessment of the Solar System Exploration Roadmap, COMPLEX commented that it is "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."[3] Through a combination of the factors listed above, the new Roadmap's scientific objectives have become even more diffuse than they were in the 1996 edition.

Given the structural deficiencies in the current Roadmap, COMPLEX reiterates its 1996 recommendation that this document must clearly indicate scientific objectives and the critical measurements that must be made to meet these objectives, describe how existing or proposed missions will make these measurements, and indicate relative priorities. Therefore COMPLEX recommends that the next Roadmap team be tasked to define a more scientifically compelling rationale for solar system exploration than that currently provided by the three Quests. As an intermediate step, COMPLEX provides some suggestions (see attached Assessment) as to how the current draft could be reorganized to make a more coherent document.

Because many of the criticisms outlined in COMPLEX's accompanying Assessment

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[3] Space Studies Board, National Research Council, "Scientific Assessment of NASA's Solar System Exploration Roadmap," letter report to Jurgen Rahe, August 23, 1996, pages 2 and 9.

result from shortcomings in the Roadmap's structure and format, they should not detract inordinately from the many favorable aspects of the program of planetary-exploration missions and supporting activities advocated in this document. 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

John A. Wood
Chair
COMPLEX

Scientific Assessment of *Exploration of the Solar System—Science and Mission Strategy*

At its November 1-5, 1999, meeting, the Space Studies Board's Committee on Planetary and Lunar Exploration (COMPLEX), chaired by John A. Wood of the Harvard-Smithsonian Center for Astrophysics, began work on an assessment of *Exploration of the Solar System—Science and Mission Strategy*,[1] the most recent update of the Roadmap of NASA's Solar System Exploration science theme.

This assessment was made at the specific request of Dr. Carl Pilcher, NASA's science program director for solar system exploration, and had two purposes. The first was a detailed comparison between the goals and objectives outlined in the Roadmap and those enunciated by COMPLEX and other relevant NRC committees. The second was to make recommendations for strengthening the Roadmap's scientific rationale and mission priorities.

ELEMENTS OF THE ROADMAP

The preparation of roadmaps is a key aspect of the strategic planning process currently adopted by NASA's Office of Space Science (OSS). Their primary purpose is to summarize the scientific objectives and programmatic recommendations put forward by each of OSS's four component groups, or science themes. The document under review was prepared for use by the Solar System Exploration science theme during OSS's ongoing strategic planning activities.

The Roadmap identifies three overarching goals, or "Quests," for solar system exploration:

1. Explain the formation and evolution of the solar system and of Earth within it;
2. Seek the origin of life and its existence beyond Earth; and
3. Chart our destiny in the solar system.

These Quests are addressed by three continuing series of spacecraft missions—the Outer Planets, Mars Surveyor, and Discovery programs—and supporting research and analysis (R&A) programs, technology development, and education and public outreach (E&PO) activities. In addition, the Roadmap recommends that two additional programmatic elements are needed if the three Quests are to be addressed in an adequate manner. These additions are a new, continuing flight program called "To Build a Planet" and a facilities initiative within the Mars Surveyor program devoted to sample handling and analysis.

Within each of the flight programs, current and planned missions are described, explicit priorities for near-term (2003-2007) to mid-term (2008-2013) new starts are outlined (except for Discovery, which, by its nature, is community driven), and some examples of possible far-term (2013+) missions are indicated. The Roadmap also includes material explaining how solar system exploration activities relate to activities within the purview of OSS's Astronomical Search for Origins and Sun-Earth Connection science themes.

The organization of the current Roadmap is significantly different from that of the edition reviewed by COMPLEX in 1996.[2] Although the Quests remain the same, the five subsidiary "Campaigns" and numerous "Portrait" missions featured in the 1996 edition have been replaced by directly linking the Quests to R&A, E&PO, and a relatively small number of prioritized missions within the various continuing mission lines.

STRUCTURE AND FORMAT OF THE ROADMAP

In general, COMPLEX found the Roadmap to be an exceedingly difficult document to review, owing, in part, to the Roadmap's format: a hybrid collection of color "vugraph"-style pages, backed up, in part, by facing pages containing supplementary text. The Roadmap is clearly intended to be presented to a reasonably sophisticated audience. Alternatively, its contents could be used selectively to provide supporting graphics for display in general presentations about NASA's planetary-exploration programs.

The Roadmap is not an easy read and is likely to be accessible only to readers with a strong background in planetary issues, processes, and recent discoveries. It is unclear whether non-specialists will understand why, for example, sampling at varying depth and location is important during a comet nucleus sample-return mission. Brief descriptions of the current state of knowledge might be useful additions to the Roadmap because they would provide some context for setting priorities among diverse planetary objects and science goals.

Additional structural problems include the lack of a table of contents or outline and the fact that many program elements are scattered seemingly randomly throughout the text. A general discussion of R&A programs (pages 12-13) is, for example, introduced in the middle of text describing Quest 1. Similarly, the material on E&PO seems out of place. The document would benefit if the general text on E&PO (pages 30-34) were moved into an introduction and the remainder (pages 35-37), in the current structure, were integrated into the sections dealing with the relevant Quests.

Without a coherent structure and cohesive introductory material the Roadmap appears to be a haphazard collection of graphics that readers must flip through back and forth in an attempt to understand the focus and goals of the proposed program of planetary exploration.

GOALS, PRIORITIES, AND SCIENTIFIC FOUNDATIONS

While the Roadmap appears to strike an appropriate balance between the broad thematic goals of understanding origins and understanding planets advocated in COMPLEX's *Integrated Strategy,*[3] the style of presentation is inadequate to convey the detailed goals, priorities, or scientific foundations motivating solar system exploration. Science justification for both existing and proposed mission lines is thin or missing and, as a result, does not substantiate NASA's goals and priorities in solar system exploration. The primary reason for this is that the Roadmap's predominantly vugraph-style format inherently limits the amount of textual information that can be presented. This problem could have been solved in large part by the addition of a narrative on the pages facing the color graphics. This option, although used in certain places, is not exercised in a consistent manner.

More seriously, the Roadmap does not provide an adequate linkage between goals, directly addressable scientific investigations, and missions. While the Campaigns fulfilled this function in the Roadmap's 1996 edition, the current version links missions and contributions from the R&A and E&PO programs directly to the three Quests. While these broad overarching statements are generally consistent with high-level goals enunciated in various SSB reports,[4] it is not clear that they provide a suitable framework for specifying scientific goals and objectives addressable by specific science investigations and for defining critical measurements.

The Roadmap's attempt to justify the highly diverse and cross-cutting nature of the program in terms of goals such as "chart our destiny in the solar system" leads to a diffuse and incoherent description of solar system exploration and its science justification. Key elements are fragmented across the Quests (as is seen in the derived outline included as an Appendix to this report), and no clear description of the proposed program's science priorities is provided. Moreover, there is no synthesis of overall goals and objectives, nor any mention of how specific elements of the program relate to those goals.

THE PROCESS OF DEVELOPING THE ROADMAP

The Roadmap contains no information about the composition of the authoring group or the process by which it was developed. Additionally, with the exception of the Mars Surveyor line, the rationale for prioritization of goals and missions is absent both within and between mission lines.

This apparent anonymity of the text is in marked contrast to the previous edition of the Roadmap, which explicitly included material on how the document was created and by whom it was written, a factor COMPLEX regarded as a plus in its 1996 review.[5] Without more information on the process used to draft the Roadmap, COMPLEX cannot comment on its fairness or credibility. The absence of details concerning the development of the Roadmap is a serious flaw.

MISSION LINES

The spaceflight component of NASA's solar system exploration program is performed within the context of several continuing line items in NASA's budget. Their establishment has brought new vitality and stability to the solar system exploration program, and NASA deserves much credit for this achievement. Three such lines currently exist, the Outer Planets, Mars Surveyor, and Discovery. The Roadmap proposes the addition of a new line, "To Build a Planet." The following subsections review what the Roadmap has to say about each of the current lines.

Outer Planets Program

The Outer Planets program, initiated as part of the "Origins" Initiative in NASA's FY 1998 budget, is, according to the Roadmap, intended to focus on "environments in the outer solar system that can provide insights into prebiotic chemistry and possible habitats for life" (page 43).

The two missions currently included in this line are the Europa Orbiter and Pluto/Kuiper Express; both address fundamental scientific goals that are broadly consistent with those outlined in recent COMPLEX reports.[6,7]

The Roadmap identifies a trio of follow-on missions: the Titan Explorer, Europa Lander, and Neptune Orbiter. The selection of the first two might appear to be premature given that they will logically build on the results from ongoing or planned missions (Cassini-Huygens and Europa Orbiter, respectively) that are still many years from completion. COMPLEX recognizes that a combination of long mission design/development periods and the extended flight times necessary to reach the outer planets mandates that work on follow-on missions must begin promptly if we are to exploit the anticipated discoveries from Cassini-Huygens and the Europa Orbiter in a timely manner. These considerations might not, however, be apparent to all readers. The Roadmap does not clearly describe the relationship between the proposed missions and their logical precursors. Without clearly stated scientific priorities and goals, the proposed follow-on missions lack context and justification.

Similarly, the text of the Roadmap makes little or no mention of the fact that major infusions of new knowledge about Europa and Titan are expected before the launch of either the Europa Lander or the Titan Explorer. Indeed, the suggestion that, for example, the Europa Lander can be ready for launch in 2008 (page 46), the same year the Europa Orbiter reaches its destination (page 45), implies that there can be little or no synergy between these two missions. (COMPLEX notes that the mission summary chart (page 106) suggests a more reasonable schedule.)

More importantly, there is nothing in the Roadmap to suggest how priorities might change if, for example, the Europa Orbiter finds no evidence for an ocean beneath Europa's icy surface. The Roadmap's scant justification for these missions and, in particular, their relationship to ongoing and approved missions is a serious flaw.

The Roadmap should clearly indicate that planning for these mid-term missions must be sufficiently flexible that they can be ready to exploit new exploratory niches uncovered by earlier missions. It would also be helpful if the Roadmap included some discussion of how mission priorities and sequences could be adjusted depending on the results from, or failure of, earlier missions.

While COMPLEX has indicated that Triton is the highest-priority target in the trans-neptunian region following the completion of a Pluto-Charon mission[8] and has provided some encouragement for additional studies of Neptune's magnetic environment,[9] the rationale for the emergence of Neptune over, say, detailed study of Jupiter, as recommended by COMPLEX,[10] should be justified more fully.

In general, as portrayed by the Roadmap this mission line seems to be suffering from an unresolved split identity. The Outer Planets program becomes "Exploring Organic-Rich Environments" early in the document (page 40) but turns back into the Outer Planets program further on (pages 101 and 103). Is the mission line devoted to organic environments or just to distant objects? The mention of "Interstellar Exploration" (on page 55) and "Interstellar Precursors" (on page 101) in the context of this program is particularly confusing. These mission concepts have deep roots in the space-physics community and have, seemingly, little to do with organic environments.[11,12,13]

The outer-planets/organic-environments duality seems to stem from the lack of focused scientific goals as the foundation for exploration and, subsequently, for the mission lines.

Alternatively, this ambiguity may reflect an unfinished transition from the early approach of cataloging planetary bodies to the more recent science-driven approach. Given COMPLEX's preference for exploration programs formulated in terms of key physical and chemical processes rather than distance from the Sun,[14] it believes that this mission line would be more compelling if explicitly directed toward the study of organic environments wherever they are found.

Mars Surveyor

Intensive exploration of Mars has long been identified as a high-priority activity by COMPLEX,[15] and the committee is encouraged to see that Mars Surveyor and, in particular, the Mars sample-return program are featured prominently in the Roadmap. Similarly, COMPLEX is pleased to see that these programs maintain their focus on activities recommended in previous reports,[16] accommodate some of the recommendations made during the committee's 1998 review of the Mars exploration architecture,[17] and point to the importance of a robust communications network.[18] COMPLEX also supports the high priority given to the proposed Mars Sample Handling and Analysis program, since such an initiative is essential both to ensure the scientific integrity of returned samples and to maximize the scientific information gleaned from the analysis of the samples.[19] The necessary facilities and protocols are required to be in place well in advance of the return of the martian samples.[20] The description of the Mars Surveyor line does perhaps the best job of linking scientific objectives to specific missions and their science goals.

Given the recent failures of Mars Polar Lander and Mars Climate Orbiter, it is not clear to what extent the contents of this part of the Roadmap will stand the test of time. Whatever the outcome of the ongoing efforts to revise the Mars exploration architecture, the scientific focus for Mars exploration remains the understanding of this planet as a possible abode of past or present life, and this requires a program of comprehensive studies aimed at understanding the origin and evolution of the martian environment.[21] A central element of these studies will be the return to Earth of samples of the martian atmosphere and soil, and, more importantly, carefully selected samples from martian rocks.[22]

It is heartening to see that the Roadmap outlines a process (page 65) by which future mission goals and strategies will be reviewed. Whatever changes are made to the Mars Surveyor program in the aftermath of the recent failures, COMPLEX expects that a thorough and open review process will be defined and applied to future Mars missions, be they those outlined in the Roadmap (i.e., Synthetic Aperture Radar, Advanced Sample Return, and Robotic Outposts), or other mission concepts arising from the ongoing architecture-review process.

Discovery

COMPLEX has long maintained that priority objectives in the planetary sciences are best addressed by a range of mission sizes.[23] The Discovery program has demonstrated that reasonable science can be achieved within the context of small- to mid-size missions.[24]

While the Roadmap emphasizes Discovery missions that are defined and led by the planetary-science community, it does not clearly state that selections are made based on compelling science and technical feasibility. Nor does the Roadmap mention that, in many instances, mission concepts emerge directly from activities supported by the R&A program. Another important aspect of Discovery that goes unmentioned is the program's ability to address

important science goals that do not fit within the scope of the Outer Planets and Mars Surveyor lines.

The close identification between Discovery and Quest 1 is probably inappropriate. The study of comets and asteroids, for example, is of direct relevance to Quests 2 and 3 and is, and will likely remain, a major focus for Discovery missions. Finally, the Discovery summary chart (page 77) would be more useful if it clearly indicated which missions had flown, which are in progress, and which are still in preparation.

To Build a Planet

The Roadmap proposes a new mission line, "To Build a Planet," designed to address questions relating to the formation and development of planetary environments. COMPLEX has very mixed feelings about this proposal. The line is justified on the grounds (page 42 and repeated verbatim on page 81) that Quest 1 is not "adequately addressed" within the current-program structures. This rationale is thin and illustrates the difficulty in using the broadly scoped Quests to justify specific scientific investigations and measurements.

The basic scientific issues this line is designed to address are, however, important items identified in past NRC reports.[25,26] Moreover, the first mission in the line, Comet Nucleus Sample Return, is consistent with prior advice from COMPLEX. Indeed, such a mission addresses the highest-priority goals identified in COMPLEX's *Integrated Strategy*.[27] COMPLEX's most serious problem with this new line is that the suite of proposed missions lacks coherence and seems to be a catchall for large missions.

While the origins and justification for a comet nucleus sample-return mission are well documented, the same cannot be said for the other two missions proposed for this line, the Saturn Ring Observer and Venus Surface Sample Return. The former was featured as a Portrait mission in a Campaign, Astrophysical Analogs in the Solar System, in the 1996 Roadmap.[28] The latter does not seem to have figured prominently in NASA's recent science-planning activities, although the European Space Agency recently published a major study concerning such an endeavor.[29] Why these missions were selected over other possible candidates is unclear and highlights the lack of discussion on how the Roadmap was created and what process was followed to select the proposed missions.

This mission line's apparent lack of coherence is heightened by the discussion of follow-on missions. Why, for example, is the Mars Geophysical Network not part of the Mars Surveyor line? Similarly, why are the Jupiter Polar Orbiter and Giant Planet Deep Probes not part of the Outer Planets/Organic Environments line?

R&A PROGRAMS AND OTHER ACTIVITIES

The R&A program is extremely important because it is the origin of both new missions and continued discovery, it supports ground-based observational and laboratory studies, and it provides the framework and foundation upon which new information from spacecraft missions is integrated into a comprehensive understanding of solar system processes. As such, its importance has been documented in various SSB reports.[30,31]

Indeed, in its review of the 1996 Roadmap, COMPLEX specifically noted the

document's failure to recognize the role of non-flight activities supported by the R&A program. Therefore, the explicit mention of the R&A program in the context of the Roadmap and, by association, the Office of Space Science's strategic-planning activities is an extremely positive factor, one strongly recommended by the SSB.[32] Unfortunately, the new Roadmap's handling of R&A and other non-mission activities such as E&PO is generally poor and not well integrated with the rest of the text.

While the general text on E&PO and that specifically related to the three Quests is consolidated in one place (pages 29-37), the text on R&A is fragmented. General text on R&A is introduced in the middle of the discussion of Quest 1 (pages 12-13) and is followed by specific text relating to Quest 1 (page 14). But the discussion of R&Ă activities relating to Quests 2 and 3 is deferred until pages 20 and 26, respectively.

SOLAR SYSTEM EXPLORATION AND OTHER SCIENCE THEMES

In the Roadmap, important linkages between the Solar System Exploration, the Astronomical Search for Origins, and the Sun-Earth Connection science themes and Astrobiology either go unmentioned or are fragmented. Text explaining how solar system exploration provides "ground truth" for the astronomical search for origins appears in the report's brief introductory section (page 6), and additional text linking these two science themes appears in the summary section (pages 108-109). However, text relating the Solar System Exploration and Sun-Earth Connection science themes appears only in the summary (pages 110-111). In addition to these linkages receiving inconsistent and cursory treatment, discussion of them is not well integrated into the preceding text.

The discussion of Astrobiology's linkages to solar system exploration is equally brief and fragmented. Astrobiology is discussed only in the context of the three Quests (pages 15-16, 21-22, and 27-28). Even then, the discussion is often cryptic. The text, for example, makes reference to Astrobiology's three fundamental questions (page 22), but nowhere is the reader told what all three questions are. Some introductory material is clearly needed. More importantly, the Roadmap's discussion of the linkages between the exploration of the solar system and Astrobiology in the context of the "Quests" rather than in the context of the "Integration of Space Science" (pages 107-111) could suggest that Astrobiology has a special status. Similarly, this treatment could be taken to imply that the goals of the Solar System Exploration theme are being justified on the basis of their relationship to the goals of Astrobiology. Scientific goals should be judged on their own merit and not on the basis of their connections to other goals of other scientific endeavors.

TECHNOLOGY ISSUES

The discussion of technological issues in the 1999 edition of the Roadmap differs significantly from that in the 1996 edition. Almost 25% of the earlier document was devoted to discussion of the key technologies and other capabilities necessary to enable the featured missions, whereas discussion of technological issues occupies less than 10% of the current document. What discussion there is is divided among the text devoted to the Outer Planets

(pages 52-53), Mars Surveyor (66-67), and "To Build a Planet" (96-97) mission lines, and the summary (104-105). There is no discussion of the technology development necessary to enable future Discovery missions. More importantly, there is no indication of how any of the development activities are prioritized, nor is there any mention of the role played by the New Millennium program and the Planetary Instrument Definition and Development Program (PIDDP).

To be fair, COMPLEX notes that the Roadmap's introduction (page 2) states that "a companion technology roadmap will be published early in the year 2000." Nevertheless, the apparent decoupling of science and missions from technology is unfortunate in that it negates what COMPLEX viewed as one of the strengths of the Roadmap's 1996 edition.[33]

FINDINGS AND RECOMMENDATIONS

COMPLEX finds that many of the missions and other activities identified in the current Roadmap address key priorities identified in reports issued by COMPLEX and other NRC committees. In particular, COMPLEX offers strong support for the Europa Orbiter, Pluto/Kuiper Express, and the Mars Surveyor and Discovery programs. COMPLEX also supports the proposed Comet Nucleus Sample Return (CNSR) mission and the new initiative concerning the handling and analysis of martian samples.

Nevertheless, COMPLEX has some significant concerns about the Roadmap and the program it presents. These concerns are, in order of priority, as follows:

1. The Roadmap does not clearly indicate the scientific objectives of solar system exploration and the critical measurements that must be made to meet these objectives, nor does it describe how existing or proposed missions will make these measurements. As a result, the scientific justification for both existing and proposed mission lines is not adequately presented. These problems stem in large part from the Roadmap's emphasis on the three broadly scoped "Quests" and are compounded by the document's lack of a coherent structure, a consistent format, a cohesive introduction, and a comprehensive supporting text.
2. The scheduling of, and the rationale for, several of the proposed missions (e.g., Europa Lander, Titan Explorer, and Saturn Ring Observer) relative to the flight programs they logically build on (e.g., Europa Orbiter and Cassini/Huygens) need to be clarified. Similarly, the priority of these missions relative to a number of possible eventualities needs to be spelled out. For example, does the Europa Lander remain in the queue if the Europa Orbiter finds no evidence of liquid water or, worse still, suffers a terminal failure?
3. The Roadmap includes no information concerning the process by which it was assembled, the identity of the authoring group, and the means by which the recommended mission sequences were prioritized.
4. The scientific rationale for the selection of the technologically challenging Venus Surface Sample Return (VSSR) mission is unclear. This is the case whether it is considered within the context of the proposed mission line, "To Build a Planet," or within the context of other possible Venus missions. Moreover, other than CNSR, many of the missions in the proposed "To Build a Planet" mission line either are not identified as high priorities in existing COMPLEX reports or might more properly be justified in other programmatic contexts.

5. The handling of non-mission activities, such as R&A programs and education and public outreach, does not adequately indicate the importance of these activities. Similarly, important linkages between the Solar System Exploration, Astronomical Search for Origins, and Sun-Earth Connection science themes and Astrobiology either go unmentioned or are obscured. In particular, discussing the relationship between the goals of the Solar System Exploration theme and Astrobiology in the context of the three Quests (pages 15-16, 21-22, and 27-28) but deferring much of the discussion of the corresponding relationships with the Astronomical Search for Origins and Sun-Earth Connection themes until later in the Roadmap (pages 107-111) might be taken to imply that Astrobiology has a special status. It could even be taken to indicate that the goals of solar system exploration are being justified on the basis of their congruence with the goals of astrobiology.

6. Detailed discussion of technological issues has been excluded.

Given the deficiencies in the current Roadmap, COMPLEX reiterates the recommendation made in its assessment of the Roadmap's 1996 edition that this document must clearly indicate scientific objectives and the critical measurements that must be made to meet these objectives, must describe how existing or proposed missions will make these measurements, and must indicate relative priorities.[34] Therefore COMPLEX recommends that the next Roadmap team be tasked to define a more scientifically compelling rationale for solar system exploration than that currently provided by the three Quests.

Such a restructuring is far beyond the scope of this brief report. Nevertheless, the new structure should, at a minimum, be organized around specific science goals and questions that can be directly related to critical measurements and focused priorities. It should, in addition, outline the rationale used for prioritization and describe how existing and proposed activities can be achieved through R&A programs, individual missions, and other activities.

As an interim step to complete revision of the Roadmap, COMPLEX suggests that a somewhat more cohesive and substantive document could be made if the text relating to R&A programs, E&PO activities, and the cross-linkages between the various science themes were handled in a more consistent and efficient manner. To this end, COMPLEX suggests that the Roadmap's introductory text be expanded to include material relating to the following:

1 The organization of the Roadmap (relevant text is not included in the current draft);

2. The process used to create the Roadmap (relevant text is not included in the current draft);

3. General material on research and analysis programs (appropriate text is to be found on pages 12-13 of the current draft);

4. General material on education and public outreach (appropriate text is to be found on pages 29-34 of the current draft); and

5. General material on how the goals of Solar System Exploration relate to the Astronomical Search for Origins (appropriate text is to be found on pages 6 and 108-109 of the current draft) and Sun-Earth Connection (appropriate text is to be found on page 110 of the current draft) science themes, and to Astrobiology (relevant text is not included in the current draft). Particular care should be taken to ensure that the linkages between the various disciplines are treated in an evenhanded manner.

Addition of this material will help make the existing Roadmap more substantive until such time as a full revision can be undertaken.

APPENDIX

Derived Outline of the December 1999 Roadmap

REFERENCES

[1] Solar System Exploration Subcommittee, *Exploration of the Solar System—Science and Mission Strategy*, Jet Propulsion Laboratory, Pasadena, California, December 1999.

[2] Roadmap Development Team, *Mission to the Solar System: Exploration and Discovery—A Mission and Technology Roadmap* (Version A), Jet Propulsion Laboratory, Pasadena, California, June 21, 1996.

[3] Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994, pages 33-34.

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