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SPACE STUDIES BOARD BULLETIN

FROM THE CHAIR

We are now in budget season. The President has submitted a FY2006 budget for NASA, and now it is up to Congress to actually appropriate the funds. Some of our worse fears about science in NASA have not been realized in the President's budget; a healthy share of the agency budget is devoted to science. However, that is only the macroscopic view. When we look in more detail there is the potential for serious damage to the future of science in NASA and for that matter to the agency as a whole.

Science in the NASA budget appears in two places: in the Science Mission Directorate (SMD), which includes all space and Earth science, and in the Exploration Systems Mission Directorate (ESMD), which includes all microgravity and life sciences. The comments here are directed at SMD, for which more detailed information is available. The microgravity and life sciences efforts appear to be evermore focused on support for long-term human exploration, but the full impact of these reductions in scope is still unclear.

SMD is to be funded in FY2006 at $5.476 billion, which represents 33 percent of the overall NASA budget of $16.456 billion. The SMD budget is approximately level-funded from FY2005. It is slated to grow to $6.798 billion by FY2010, which relative to the projected overall budget for NASA in that year, represents about 38 percent.

Comparisons with previous budgets for science are somewhat difficult to make due to reorganizations and changes in accounting for launch costs and civil service salaries. Throughout much of NASA's history, science considered its fair share of the NASA budget to be 20 percent. In the late 1990s and early 2000s, the percentage for science did grow. However, this was an era when human space flight lacked a defendable purpose, and so science was able to demand and receive a larger share. By historical measures, then, SMD now appears to be allocated a healthy share of the overall NASA budget, and with human space flight now having clear goals, the percentage for science is highly unlikely to become a much larger share of NASA than the projected growth to 38 percent.

It would, of course, have been desirable for the NASA budget as a whole to grow at a more rapid pace since then, even at a fixed percentage, the science budget would also experience more rapid growth. Unfortunately, with limits on domestic discretionary spending, NASA is growing at only a few percent per year. In fact in FY2006, the NASA budget increases by $0.5 billion less than was projected just a year ago.

In evaluating the FY2006 budget for SMD the most important comparison is with expectations. In the FY2004 budget for NASA, which predates the Vision for Space Exploration, space and Earth science were projected to have combined budgets of $6.550 billion in FY2006, compared with $5.476 in the actual FY2006 request. Even after accounting for the transfer of the Prometheus nuclear technology program from SMD to ESMD, SMD would have to have a larger share of the NASA budget than is now possible to support the FY2006 program that was expected in FY2004, plus the new initiatives for the Moon and Mars.

Most of the growth that was projected in FY2004 was in space science; Earth science was projected to have a declining budget. In many ways, Ed Weiler, the former Associate Administrator for Space Science, was too successful. He sold programs that required a growth in funding for science that is not now attainable.

A similar situation happened to science in the early 1990s. There were three major new starts: AXAF (now Chandra X-ray Observatory) in 1989; the CRAF/Cassini comet science and Saturn exploration mission pair in 1990; and the major Earth Observing System program in 1991. To accomplish these programs the budget

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FROM THE CHAIR

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for space and Earth science needed to increase at greater than 10 percent per year throughout the 1990s. Such an assumption was not unreasonable at the time; e.g. the 1990 Presidential Advisory Committee on the Future of the U.S. Space Program, chaired by Norm Augustine, assumed that the overall agency budget would grow at 10 percent per year.

However, the growth in the science budget and in the overall agency budget in the early 1990s did not occur. The response of NASA leadership at that time was to make surgical cuts to missions and to protect the base of small missions, Research & Analysis (R&A) grant funding, and Mission Operations & Data Analysis (MO&DA). AXAF was descoped; CRAF was cancelled; and EOS was subjected to a major downsizing. The only new missions added to the budget were relatively small missions such as the Discovery program for solar system exploration.

In FY2006, NASA leadership appears to be taking a different tactic. They are making every attempt to preserve the space science missions in development. There appears to be some concern that the cancellation or serious delay of space science missions under development will be seen as having been caused by the exploration initiative, which would be a challenge to its political support.

With the budget for science limited by the growth in the overall NASA budget, missions in development protected from cuts, and new lunar and Mars missions added, there are limited places to go for relief. Consequently, operating missions are being cut; e.g. MO&DA funding for missions such as Voyager and Ulysses are to be eliminated in FY2006. Small R&A grants for theory, modeling, data analysis, and technology development are seriously threatened, as evidenced by the recent cancellation of some expected proposal solicitations.

There is a fundamental question here. Is NASA's job to do science or simply to fly new missions? The two goals are not necessarily compatible. Within limited funds the science program may be better optimized by getting the maximum benefit from ongoing and irreplaceable missions, such as Voyager and Ulysses, than by undertaking new adventures. Science is conducted through the R&A and MO&DA programs, and the value of the investment in missions can be realized only if the accompanying programs necessary for their success are healthy.

There is also a practical issue here: there is no flexibility in the proposed NASA science budget. Congress will inevitably earmark the budget for several hundred million dollars. There needs to be a plan for how to absorb the earmarks without hurting the foundation of the program, the R&A program.

Finally, it is very much not in NASA's long-term interest to cut its base, the supporting MO&DA and R&A programs. These are the programs that support the training of the next generation of scientists and engineers at universities.[1] The workforce problem facing NASA is potentially crippling. It will take an entire new generation of scientists and engineers, perhaps 50,000-75,000 new participants, to execute the President's vision for space exploration. They will be trained in the nation's universities, supported by the R&A and MO&DA programs. To cut here is to strangle the pipeline of students on whom the future of NASA will depend.

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[1]The roles and importance of research and data analysis programs are discussed in detail in the 1998 SSB report, *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis*.

DIRECTOR'S COLUMN

The first quarter of 2005 certainly opened a new page in NASA's history. NASA Administrator Sean O'Keefe departed in mid-February after serving in the position for slightly more than three years. Among the actions for which he will be remembered are his efforts to address management and cost problems with the International Space Station, technical and management responses to the Columbia space shuttle accident that included a major reorganization of the agency, the formulation and early execution of a new administration space policy, and the introduction of a new agency strategic planning process. Then in mid-March the President selected Michael Griffin, an aerospace engineer with extensive space program experience, to succeed O'Keefe. Griffin will bring first-hand perspectives from both industry and government in space activities that cover the full range from defense and national security to space science. Griffin is seen as an enthusiastic, articulate, and thoughtful supporter of space exploration.

Based on early reactions to his nomination, Griffin's confirmation by the Senate seems very likely, and when he is able to take the reins of NASA he will have to confront a sizable array of challenges. Among the first of those will be elaboration and defense of the administration's FY2006 budget request. At first glance, the NASA budget outlook is comparatively robust and rosy. The R&D portion of NASA's budget is slated for a 5 percent increase, which would be the highest of any agency except for the departments of Transportation and Homeland Security. For comparison, R&D budgets at NSF and NIH are slated to grow by only 3 percent and 1 percent, respectively; Commerce R&D is proposed for a 1 percent drop as is also the case for total federal non-security R&D spending. Consequently, when one examines the big picture NASA certainly seems to have been given favorable treatment. Furthermore, when one looks at the longer-term projections, the total budget of the NASA Science Mission Directorate is slated to be 33 percent of the total NASA budget in FY2006 and to grow to 38 percent of the total by 2010. The latter number will be an historical high.

Upon peeling the budget onion to the next level of detail one begins to discover a mixture of good news and bad news. The Science Mission Directorate is slated for no growth from FY 2005 to 2006. Instead all the growth in NASA R&D is in the Exploration Systems Mission Directorate. There are reductions in aeronautics, in the former biological and physical research program for the ISS (now called human systems research and technology), and in Earth science and sun-Earth connections (now combined to form the Earth-sun system research program). Among the potential impacts in science are delays (or cancellations) in space missions for disciplines other than solar system exploration, reductions in research and data analysis resources, and elimination of all fundamental microgravity research.

There are other significant aspects of the long-term NASA budget picture. NASA's budget request presents both the specific funding levels proposed for FY2006 and projected program funding levels for 2006-2010, with the latter being known as the "budget run-out." NASA's run-out as shown in the FY2006 request projects a growing budget, but the growth is lower than was projected in the FY2005 budget by a cumulative total of about $2.5 billion. The fact that the budget is projected to grow provides evidence of the administration's support for the space program. The fact that the amount of growth has decreased compared to last year's projections is strong evidence of the impact of deficit reduction policies that are likely to become more important in years to come. When one looks at where reductions are proposed to be made to accomplish the decreases in the 2006-2010 run-out, there is evidence for how the administration priorities reflect the new Vision for Space Exploration. In particular, the largest portion of the $2.5 billion reduction in run-out will come from Earth and space sciences (nearly $1.2 billion), the second largest bite will come from aeronautical research ($700 million), and the smallest bite will be in the budget from the Exploration Systems Mission Directorate (just over $200 million). Finally, in terms of what the budget proposal portends for space research, examining the details shows that solar system exploration missions are slated to grow by about 60 percent over the five-year period, while the total budgets for astrophysics, Earth science, and Sun-solar system connection research programs will stay practically flat (total growth of only 4 percent from 2006-2010).

The picture summarized above suggests to me that the space community must be prepared to confront two major challenges. First, how can the space program hold its own in a tight budget environment? Space research and exploration will have to compete for priority and support in a highly competitive federal budget climate in which growth will be increasingly rare and pressures for deficit-reduction spending constraints will be great. Second, how can the space program achieve the administration's exploration goals and maximize the return on the tax payers' investment? The return on investment is measured in many ways, which include scientific and technological advancement, public inspiration, economic impact, and more. To remain competitive in the face of challenge #1, the space program will have to demonstrate discipline in the setting of priorities in a very competitive internal environment.

The SSB's recent report, *Science in NASA's Vision for Space Exploration*, presented at least a partial solution to dealing with those two challenges—i.e. demonstrating competitiveness in the larger federal scene and resolving competitions for internal decision making. In particular, the report recommended a set of guiding principles, which said, in part

- Both robotic spacecraft and human spaceflight should be used to fulfill scientific roles in NASA's mission to explore. When, where, and how they are used should depend on what best serves to advance intellectual understanding of the cosmos and our place in it and to lay the technical and cultural foundations for a space-faring civilization.
- The targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond.
- The targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what is our ultimate destiny.

In short, space exploration should be broad, it should be about expanding our understanding of the universe and our place in it, and it should be directed at making the most profound impacts possible on our knowledge and our society. Only those endeavors that best meet that test should earn priority. How forthrightly NASA, the administration, and the Congress apply that test, or alternative criteria, will have much to do with the shape and content of space activities and the space community for the next decade. Sound decisions can ensure meaningful progress and sustain public support, momentum, and capability for the future. The challenges are very real.

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BOARD AND COMMITTEE NEWS

- The **Space Studies Board** (SSB) held its 145th meeting on February 28-March 2, 2005, at the National Academies Keck Center in Washington, DC. One major topic for discussion was the administration's fiscal year 2006 budget proposal. Guest speakers included David Radzanowski, Office of Management and Budget; William Jeffrey, Office of Science and Technology Policy; and David Goldston and Richard Obermann, House Science Committee staff. Gregory Withee, NOAA-NESDIS, briefed the Board on NOAA's Satellite and Information Service FY 2006 Budget request. NASA Chief of Staff John Schumacher, presented an overview of the Vision for U.S. Space Exploration and the NASA transformation, followed by Al Diaz, associate administrator for science, who briefed the Board on the status of NASA's Science Mission Directorate and the FY2006 budget. Steve Isakowitz, NASA deputy associate administrator for the Exploration Systems Mission Directorate also spoke with members. The SSB Board dinner was held in the National Academies Koshland Museum.

Marc Allen, NASA Science Mission Directorate, opened the Tuesday, March 1st session with a briefing on NASA's strategic planning and the status of the strategic roadmaps. The NRC membership nomination process is currently in progress for the four panels being formed to review the NASA roadmaps (Science, ISS, Spaceflight Systems, and Education).

Another special guest during the meeting was Mengxin Sun, Embassy of the People's Republic of China, who discussed China's progress in space exploration.

The Board discussed a number of statements of task for new SSB studies and also reviewed the status of on-going studies and committee activities.

The next meeting of the Board will be June 7-9, 2005, at the Jet Propulsion Laboratory in Pasadena, CA.

- The **Committee on Astronomy and Astrophysics** (CAA) did not meet during the quarter. In the fall of 2004 CAA assisted in organizing the **Committee on the Mid-Course Review of the Astronomy and Astrophysics Decadal Vision** to prepare a letter report that would review scientific discoveries and technical advances in astronomy and astrophysics over the 5 years since publication of the decadal survey, *Astronomy and Astrophysics in the New Millennium,* and address the implications of those developments and recent changes in the federal program. The committee's report, "*Progress in Astronomy and Astrophysics Towards the Decadal Vision,"* was released on February 11. CAA will meet next on May 19-20 in Washington, DC.

- The **Committee on Planetary and Lunar Exploration** (COMPLEX) did not meet this quarter. At its next meeting COMPLEX will review several of NASA's strategic roadmaps. Three new members are being appointed to assist with the roadmap review. Reta Beebe's term as committee chair will be extended to December 2005. COMPLEX has several new projects in the planning stages, including defining a "New Vision for Lunar Science" and a study on "Inner Planet Interconnections." Both projects have been discussed with NASA officials, and the committee is waiting final word. Study Director David Smith attended the Mars Exploration Program Analysis Group (MEPAG) meeting on February 16-17, 2005 in Arlington, VA on behalf of COMPLEX. The next meeting of COMPLEX will be April 18-20 in Washington, DC.

- The report of the **Task Group on Organic Environments in the Solar System** is in external review. Approval and release are planned for summer 2005.

- The **Task Group on the Limits of Organic Life in Planetary Systems** (LIMITS) met for the final time on March 14-16, 2005 at the National Academies' Beckman Center in Irvine, CA. This meeting was devoted to an extensive examination of extrasolar planetary environments and their potential biomarkers and to an update on the initial results from the Cassini-Huygen's mission investigations of Titan. In addition to presentations, the task group made extensive revisions to the draft outline, split into writing groups, and began to integrate individual ideas to form what will be the first draft of the report. This report is due to enter the NRC review process in late spring 2005.

- The **Committee on the Origins and Evolution of Life** (COEL) met on February 9-11 at the National Academies Keck Center in Washington, DC. The committee's report, *The Astrophysical Context of Life*, was presented to NASA officials by committee co-chair J. Craig Wheeler on March 3, 2005 and released to the public in pre-publication format on the March 8. The committee has received a request from NASA's Planetary Protection Officer John Rummel to prepare a letter report commenting on the need to revise the planetary protection requirements for missions to Venus. In addition, a committee proposal to initiate a major new study to define an astrobiology strategy for the exploration of Mars has been drafted and favorably received by NASA. Study Director David Smith addressed the NRC Communications Advisory Committee on nascent SSB/Joseph Henry Press plans for a popular book based on COEL's forthcoming Mars study.

COEL will meet next on May 31–June 2 in Woods Hole, MA. The meeting will be devoted toward work on the roadmap reviews and the Venus project. Progress is under way on the selection of new committee co-chairs whose terms end this year.

- The **Steering Committee for Space Science Enabled by Nuclear Power and Propulsion** and panels have completed all of the meetings devoted to the Phase-I report. Progress on synthesizing the work of the 3 science panels is almost complete as is the drafting of the chapter contributions by the steering group. Work on integrating all of the drafted material is scheduled for completion in early spring.

- The **Committee on Solar and Space Physics** (CSSP) met on February 7-9 at the University of Colorado's Laboratory for Atmospheric and Space Physics in Boulder, Colorado. The meeting agenda focused on (a) planning for the committee's participation in the review of NASA's sun-solar system roadmap and (b) planning for future studies to be organized by CSSP. Barbara Giles from NASA/GSFC and Tim Killeen Director, NCAR provided background on the NASA roadmap process. Ron Turner from ANSER Co., Jeff Forbes, University of Colorado, and (by telephone) Richard Behnke, Head of the NSF's Upper Atmosphere Research Section, made presentations that were relevant to planning for new studies. The committee also met with the Director of NOAA's National Geophysical Data Center, Chris Fox.

The committee discussed 3 potential new studies:

1. A workshop and possible study to examine the radiation environment in the solar system and how it might impact robotic and human exploration.
2. A study that would focus on the Nation's current and future ability to manage severe space weather events and mitigate their deleterious impacts.
3. A workshop or study on comparative planetary environments (atmospheres and magnetospheres).

Committee member John Foster presented a revised draft of the report on the Workshop on Distributed Arrays of Small Instruments (DASI) for application to solar-terrestrial physics. A final version of the report is expected to enter the NRC review process in spring 2005.

- The **Committee on Earth Studies** did not meet during the quarter, but committee members continued to work on completion of the report *Extending the Effective Lifetimes of Earth Observing Research Missions*. The report is expected to enter NRC review in spring 2005.

- The Steering Committee for **Earth Science and Applications from Space** (ESAS) held its second meeting on January 5-6 at the National Academies Beckman Center in Irvine, California. Most of the meeting was devoted to generation of an outline and initial draft of an interim report to be published in spring 2005. This report will address near-term issues that require attention prior to publication of the committee's final report, due in late 2006.

In order to obtain the greatest possible input of ideas from the community about potential mission concepts addressing Earth science research and applications, the steering committee also released a request for information (RFI). The committee is especially interested in ideas for missions or programs that are directly linked to societal needs and benefits. Responses to the RFI are due by May 16, 2005.

The study is organized with a steering committee ("executive committee") overseeing and synthesizing the work of seven thematically-organized panels:

1. Earth Science Applications and Societal Needs
2. Land-use Change, Ecosystem Dynamics and Biodiversity
3. Weather (incl. space weather and chemical weather)
4. Climate Variability and Change
5. Water Resources and the Global Hydrologic Cycle
6. Human Health and Security
7. Solid-Earth Hazards, Resources, and Dynamics

During this quarter memberships on 6 of the panels were approved by the NRC.

Members of the steering committee gave presentations at the annual meeting of the American Meteorological Society and at meetings of NASA roadmap and Earth science advisory committees. The committee has also established a web site at http://qp.nas.edu/decadalsurvey where interested members of the community can stay up to date with the study and provide views to the committee.

- The **Committee on Space Biology and Medicine** (CSBM) was not active during this period, except for various tracking and dissemination activities such as providing requested materials and information on prior reports or assistance to related studies by other committees. Work did begin under CSBM auspices to organize an independent NRC review of NASA's strategic roadmap for research on the International Space Station.

- The **Committee on Microgravity Research** (CMGR) was not active during this period, except for various tracking and dissemination activities such as providing requested materials and information on prior reports.

- The **Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope** provided congressional testimony regarding its report *Assessment of Options for Extending the Life of the Hubble Space Telescope*. Committee chair Louis Lanzerotti testified before the House Science Committee on February 2. Dr. Lanzerotti's testimony (see page 6), was supported by the comments from committee members Charles Bolden, Joe Rothenberg, and Joseph Taylor. The committee responded to follow-up questions after the hearing. The committee's final, edited report was released on February 28. Copies will be available on CD-ROM in mid-spring.

- The **Committee on Preventing the Forward Contamination of Mars** (PREVCOM) is continuing to prepare its report for external review. A prepublication version of the report is expected in late spring 2005.

- The **Committee on Principal-Investigator (PI)-Led Missions in the Space Sciences** met on February 1-3, 2005 at the National Academies' Arnold and Mabel Beckman Center in Irvine, CA. The meeting objectives were to obtain perspectives from PIs, project managers, and agency officials; work on the first draft of report; draft findings and recommendations; and agree on a schedule for report development.

Al Diaz, Associate Administrator for Science in NASA's Science Mission Directorate, answered the committee's questions on PI-led missions via videoconference. Other presentations included interviews with PIs and project managers (PMs) on PI-led Missions and perspectives from Charles Elachi and Tom Gavin, Jet Propulsion Laboratory (via teleconference), Michael Malin, Malin Space Science Systems, Edward Stone, Caltech, Paul Hertz, NASA Headquarters, Anthony Comberiate, GSFC, and William Cantrell, NASA Headquarters.

The committee is continuing to work on its draft report.

- The **Committee on Space Research (COSPAR)** held its annual business and program meetings March 21-24, 2005. COSPAR's Program Committee met to begin to organize the scientific program for 2006 Scientific Assembly to be held in Beijing, China. The COSPAR Bureau met to review COSPAR business and operations, and the Publications Committee met to consider issues relevant to *Advances in Space Research*, COSPAR's scientific journal, and the *COSPAR Information Bulletin*. Prior to its business meetings, COSPAR held a meeting to follow up on "The Future of COSPAR" brainstorming session held last July after the COSPAR scientific assembly in Paris. Since the July meeting, task groups have been considering specific aspects of the COSPAR organization—international cooperation, relations with external organizations, scientific structure, scientific vision for the future, capacity-building, developing nations, and young scientists and students—and how COSPAR should handle or change those responsibilities in the future. Representatives of the task groups reported on their conclusions. COSPAR's Bureau and Program Committee will meet next in the spring of 2006.

- The **Space Studies Board** (SSB), working jointly with the **Aeronautics and Space Engineering Board** (ASEB), is organizing independent reviews of strategic road maps that are being developed by NASA's Advanced Planning and Integration Office. These strategic roadmaps will present specific objectives, priorities, milestones, decision points, and implementation approaches in support of the agency's thirteen top-level objectives. The reviews will evaluate the roadmaps in terms of responsiveness to NASA's vision, mission, and major strategic goals; intrinsic scientific merit and potential for contributing decisive or transformational technological or scientific advancements; coverage of cross-cutting issues; clarity of priorities and the process for setting priorities; and realism with respect to necessary resources, technologies, facilities, and schedule. Six separate review panels will be established to review individual roadmaps or clusters of related roadmaps during the second and third quarters of 2005.

CONGRESSIONAL TESTIMONY

Statement of

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and
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and

Chair, Committee on Assessment of Options to Extend
the Life of the Hubble Space Telescope
National Research Council
The National Academies

Before the
Committee on Science
The U.S. House of Representatives
Hearing on
"Options for Hubble Science"

FEBRUARY 2, 2005

Introduction

Mr. Chairman, Ranking Minority Member, and members of the committee: thank you for inviting me here to testify today. My name is Louis Lanzerotti and I am a professor of Physics at the New Jersey Institute of Technology and a consultant for Bell Laboratories, Lucent Technologies. I appear today in my capacity as chair of the National Research Council (NRC)'s Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope.

As you know the NRC is the unit of the National Academies that is responsible for organizing independent advisory studies for the federal government on science and technology. In early 2004 the NRC was asked by Congress and NASA to examine the issues surrounding the cancellation of the final servicing mission (SM4) for the Hubble Space Telescope and to consider both the value of preserving Hubble and the potential methods for doing so. Specifically called out in the tasking was a requirement to survey the potentials of both on-orbit and robotic intervention. The National Research Council formed a committee under the auspices of the Space Studies Board and the Aeronautics and Space Engineering Board to respond to this request.

After detailed examination of the astronomical evidence that was presented to it, the committee concluded that NASA should commit to a Hubble serving mission that accomplishes the objectives of the originally planned SM-4 mission. This includes the emplacement of two new instruments, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera-3 (WFC3), as well as refurbishments of those spacecraft subsystems that are required to preserve the health and safety of the telescope, both for science as well as for eventual safe de-orbiting.

The committee's principle conclusions related to the mission risk of servicing Hubble were:

> *The need for timely servicing of Hubble, due to lifetime limits on various engineering subsystems, imposes difficult requirements on the development of a robotic servicing mission. The very aggressive schedule, the complexity of the over-all mission system design (which is in a rudimentary state), the current low level of technology maturity (other than the yet-to-be flown International Space Station (ISS) Special Purpose Dexterous Manipulator System (SPDM) and Grapple Arm (GA; essentially the Shuttle Remote Manipulator System (RMS)), and the inability of a robotics mission to respond to unforeseen failures that may well occur on Hubble between now and a robotic servicing mission make it highly unlikely that the science life of HST will be extended through robotic servicing.

> *A shuttle servicing mission is the best option for extending the life of Hubble and preparing the observatory for eventual robotic de-orbit; such a mission is highly likely to succeed. The committee believes that this servicing mission could occur as early as the seventh shuttle mission following return to flight, at which point critical shuttle missions required for maintaining the ISS will have been accomplished.

It is obvious that a robotic servicing mission to Hubble would involve no risk to astronauts. However, the committee was informed that the nation is committed to 25 to 30 human shuttle flights to the International Space Station (ISS). In reviewing all of the data presented to it, and in making use of the expertise of the committee's members who have deep experience in human space flight as well as in managing the nation's human space flight program,

> *The committee concluded that the difference between the risk faced by the crew of a single shuttle mission to the ISS—already accepted by NASA and the nation—and the risk faced by the crew of a shuttle mission to HST is very small. Given the intrinsic value of a serviced Hubble, and the high likelihood of success for a shuttle servicing mission, the committee judges that such a mission is worth the risk.

As I noted, these conclusions were reached after a considerable, in-depth examination of technical data and documents, presentations by expert witnesses, extensive exchanges and consultations with NASA, industry and academic colleagues, and multiple site visits to the Goddard Space Flight Center and the Johnson Space Flight Center. The committee members have outstanding, world-recognized credentials in not only the diverse fields relevant to this study (ranging from risk assessment to astronomy) but also in their decades of direct, practical, experience with the NASA spacecraft systems and programs that were being evaluated. Two of my committee members, General Charles Bolden, a veteran former astronaut whose shuttle missions include the deployment of the Hubble

Space Telescope, and Mr. Joseph Rothenberg, former Associate Administrator of Spaceflight at NASA and former director of the Goddard Space Flight Center, are present with me today and are available to answer questions.

Before I continue I would like to note, and indeed stress, that when this study was initiated, I found a broad diversity of opinion among the committee members on both the question of whether Hubble should be preserved, and if so, which method of doing so was preferable. After all, from my personal experience and the experience of some members of the committee, almost no space researcher is ever in favor of turning off an operating spacecraft that is continuing to return excellent data. Hence, some members of the committee questioned at the outset of our study the very premise of keeping Hubble alive. It was only after a vigorous and painstaking exploration of the information presented to us, and considerable questioning analysis, that the committee reached the conclusions that are found in our report. Those conclusions were reached unanimously, and without reservation, by our entire membership.

Of the many issues considered by the committee, I have been asked to focus today on 1) Hubble's contribution to science and what its loss or performance interruption would mean, and the 2) the comparative strengths and weaknesses of a shuttle servicing mission, a robotic servicing mission, and a rehosting mission. I will therefore devote the remainder of my testimony to these issues.

The Past and Future Contributions of Hubble

Over its lifetime, the HST has been an enormous scientific success, having earned extraordinary scientific and public recognition for its contributions to all areas of astronomy. Hubble is the most powerful space astronomical facility ever built, and it provides wavelength coverage and capabilities that are unmatched by any other optical telescope currently operating or planned. Much of Hubble's extraordinary impact was foreseen when the telescope was being planned. It was predicted, for example, that the space telescope would reveal massive black holes at the centers of nearby galaxies, measure the size and age of the observable universe, probe far enough back in time to capture galaxies soon after their formation, and provide crucial keys to the evolution of chemical elements within stars.

All of these predicted advances have been realized, but the list of unforeseen Hubble accomplishments may prove even greater. Hubble did discover "adolescent" galaxies, but it also saw much farther back in time to capture galaxies on the very threshold of formation. Einstein's theory of general relativity was bolstered by the detection and measurement of myriad gravitational lenses, each one probing the mysterious dark matter that pervades galaxies and clusters of galaxies. Gamma-ray bursts had puzzled astronomers for more than 20 years; in concert with ground and X-ray telescopes, Hubble placed them near the edge of the visible universe and established them as the universe's brightest beacons, outshining whole galaxies for brief moments. Perhaps most spectacularly, Hubble confirmed and strengthened preliminary evidence from other telescopes for the existence of "dark energy," a new constituent of the universe that generates a repulsive gravity whose effect is to drive galaxies apart faster over time. The resulting acceleration of universal expansion is a new development in physics, possibly as important as the landmark discoveries of quantum mechanics and general relativity near the beginning of the 20th century.

Closer to home, Hubble has zeroed in on our own cosmic past by uncovering virtual carbon copies of how the Sun and solar system formed. Dozens of protoplanetary disks have been found encircling young stars in nearby star-forming regions of the Milky Way. The sizes and densities of these disks show how surplus dust and gas collect near infant stars to form the raw material of planets. Dozens of large, Jupiter-like planets have been discovered, initially by other telescopes but recently by Hubble using a new and more precise method. Measuring the tiny drop in light as a planet transits the disk of its parent star, the new technique could lead to a method for discovering Earth-like planets—a discovery with tremendous long-term implications for the human race.

I would like to stress that results from Hubble – its pictures and the new concepts that have flowed from these images – have captured the imagination of the general public, not only in our country but around the world. Hubble has been one of the most important outreach instruments in terms of its contributions to public awareness of science and of the universe in which we live.

Fascinating as they are, the scientific returns (and the public interest and excitement) from Hubble are far from their natural end. With its present instruments the telescope could continue probing star formation and evolution, gathering more data on other planetary systems, revealing phenomena of the planets and comets in our own solar system, and exploring the nature of the universe at much earlier times.

Two new instruments, already built for NASA's previously planned servicing mission (SM-4), would amplify the telescope's capabilities by allowing qualitatively new observations in two underexploited spectral regions. Such rejuvenation via new instruments has occurred after every Hubble servicing mission, and the next one promises to be no different. Wide Field Camera-3 (WFC3) would increase Hubble's discovery efficiency for ultraviolet and near-infrared imaging by factors of 10 to 30. The UV channel coupled with the camera's wide field of view will image the final assembly of galaxies still taking place in the universe. The near-infrared channel of WFC3 favors discovery of the very youngest galaxies, whose light is maximally red-shifted. The available UV, visible, and near-IR channels will combine to give a sweeping, panchromatic view of objects as diverse as star clusters, interstellar gas clouds, galaxies, and planets in our own solar system.

The second new instrument, the Cosmic Origins Spectrograph (COS), will increase Hubble's observing speed for typical medium-resolution ultraviolet spectroscopy by at least a factor of 10 to 30, and in some cases by nearly two orders of magnitude. Ultraviolet spectra carry vital clues to the nature of both the oldest and the youngest stars, yet UV rays are totally invisible to ground-based telescopes. COS will fill important gaps in our understanding of the birth and death of stars in nearby galaxies. Even more impressive, COS will use the light of distant quasars to spotlight previously undetectable clouds of dispersed gas between nearby galaxies, thereby mapping in unprecedented detail the properties of the so-called "cosmic web."

The future accomplishments I have described, and the many unforeseen discoveries that are impossible to predict but certain to occur, are what would be lost if Hubble was not serviced or replaced. It might be argued, of course, that the universe will be here into the future for other space missions to explore further. However, a number of NASA space astronomy missions presently in flight as well as planned, including the X-ray satellite Chandra and the infra-red satellite Spitzer, would not be as productive as they can be if synergistic data from Hubble were not to be available for analyses. The most recent Decadal Survey of Astronomy has predicated its recommendations for the future of the research field, and for the future facilities that would be needed for future advances, on the existence of Hubble data and its use in conjunction with other NASA space astronomy missions. My colleague Professor Joseph Taylor, a Co-Chair of this Decadal Survey, is here today and can address this aspect of Hubble much better than can I.

It is important to recognize that a central issue in the discussions that entered into our committee's conclusions is that the Hubble has a limited life; it was designed from the outset to be serviced periodically. A lengthy delay in servicing (the technical details are described in detail in our report) could result in a permanent loss of the telescope and even in a telescope orientation that would prevent ultimate safe de-orbit.

As shown in our report, it is most likely that an interruption of science operations will occur due to gyroscope failure some time in mid- 2007 unless servicing occurs. The ultimate, irreversible, failure of the telescope in the next several years is dependent on battery lifetime. Our committee spent a great deal of time investigating the conditions of the batteries (with a sub group of the committee speaking to NASA and other engineers, including the battery manufacturer, and studying data from battery life tests in a laboratory) and concluded that the window for battery failure that would end science operations opens in about May 2007. The window for potential vehicle failure opens in 2009. While there are many considerations in coming to these dates, there are few options beyond servicing for improving the outcome. The batteries themselves are not greatly affected by lighter loading that might be possible by early termination of science operations since operations will already be terminated at an early date due to loss of gyros.

Comparison of Robotic Servicing, Shuttle Servicing and Rehosting

Let us leave aside for the moment the issue of placing the Hubble instruments on some other spacecraft and begin with the realization that, given the predicted failure of the on-board gyros, HST most likely will need to terminate science operations by mid-2007. Based on this engineering determination which we believe to be correct, any servicing mission, shuttle or robotic, must be accomplished by the end of 2007 at the latest to prevent an interruption in science. A delay past 2007 not only results in increasing odds that the repair mission will meet an impaired Hubble when it launches. In the case of a robotic mission, it also means a growing reduction in the remaining lifespan of the serviced Hubble because, unlike a human servicing mission, it will be incapable of correcting most types of avionics system failures. A 2009 robotic mission would occur at a time when the telescope is already at the fifty percent risk point.

Even NASA's most optimistic projections places the robotic mission in December 2007, and this estimate was made when the NASA project hoped to receive full funding for development in both 2005 and 2006, something that has not occurred. Because the impact of reduced funding is always schedule delay, and often increased risk, there is a low probability of being able to undertake a successful robotic mission in time to save HST, even if much of the hardware has already been assembled and all of the systems testing had been successfully accomplished.

Now, let us compare a robotic servicing mission with a shuttle servicing one. Some of the important strengths of a shuttle servicing mission are (1) it has been done successfully before – four times in fact – so there is no new development required; (2) all of the instruments and replacement equipment have been built or can be made ready, so there is low schedule risk; (3) numerous life extension upgrades that are not feasible on a robotics mission could be carried out; (4) the shuttle has a proven capability for repairing Hubble with one hundred percent success history from four missions; and (5) a human mission has the unique ability to respond to last-minute requirements, usually driven by unforeseen failure (such as the need for new magnetometer covers that occurred on SM-1). In addition, and very importantly, the SM-4 mission could reduce the risk and cost of the eventual de-orbit mission for Hubble by pre-positioning a docking mechanism and associated fiducials on the aft end of the telescope so that the rendezvous and docking of the de-orbit module would be greatly facilitated over the uncooperative target that the telescope presently offers to any robot approaching it. The main weaknesses in a shuttle servicing mission are that the schedule depends on successful shuttle Return To Flight (RTF), and there is a small crew safety risk by flying one shuttle mission in addition to the 25 to 30 that are estimated by NASA as required for completion of the ISS. The additional shuttle mission would also delay ISS assembly by 3 to 5 months, thereby increasing slightly shuttle program costs (in comparison to total shuttle program costs) at the end of the shuttle life, currently projected for 2010.

The strengths of a robotic mission are (1) it avoids the risks to astronauts of one additional shuttle flight; (2) it is exciting technology; and (3) some of the technology may have applications to other space activities. The weaknesses are primarily those associated with successfully achieving an extremely ambitious mission on an aggressive schedule, and the risk to HST (not only to HST science but also to eventual successful de-orbit) of using it as a target vehicle for the demonstration of unproven technology. It also has very large costs, both near and far term costs; an estimate of $2.2 billion (or more including launch costs) was provided to NASA by the Aerospace Corporation. Those members of the committee who are familiar with such costs believe that this number is plausible.

From the risk mitigation viewpoint, the committee stated in our report that the planned use for the robotic servicing mission of the mature ISS robotic arm and robotic operational ground system helps reduce both the schedule risk and the development risk for this mission. However, the committee found many other serious challenges to the development of a successful robotic mission. Some of these challenges are due to the simple fact that Hubble was not designed to be serviced robotically, and thus has hardware features that are designed for human, not robot, interactions. Challenging issues for a successful robotic mission include:

- Technologies required for close proximity operations and autonomous rendezvous and capture of the telescope have not been demonstrated in a space environment.
- The control algorithms and software for several proposed systems such as the laser ranging instrument (lidar) and the camera-based control of the grapple arm are mission-critical technologies that have not been flight-tested.
- Technologies needed for autonomous manipulation, disassembly and assembly, and for control of manipulators based on vision and force feedback have not been demonstrated in space.
- The Goddard HST project has a long history of Hubble shuttle servicing experience, but little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the proposed HST robotic servicing mission.
- The Committee found that the Goddard HST project had made advances since January 2004. However, the Committee also found that there remain significant technology challenges and – very significantly – major systems engineering and development challenges to successfully extend the lifetime of HST through robotic servicing.
- The proposed Hubble robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The committee concluded that the likelihood of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

Rehosting

Rehosting of the two new instruments COS and WFC3 was the final option I was asked to discuss in my testimony today. In theory, the flight of these existing instruments on a new astronomy mission would be a possible means of obtaining some of the science that would otherwise be lost if Hubble were not repaired through a shuttle servicing mission. The information that was provided by NASA to the committee on possible re-hosting options was very sketchy, certainly not as defined and as detailed as was much of the technical information available for servicing Hubble. One clear advantage of any re-host mission is that it would use a spacecraft that employed current era technologies. Possible re-hosting missions could be to either a low Earth orbit (LEO), such as the one that Hubble is currently flying in, or to some other orbit, such as geosynchronous or a Lagrangian point. It was unclear to the committee which, if any, of these orbits was under any serious consideration by NASA. Thus, I have to speculate somewhat as to what might be being proposed today, some four months after the committee's last meeting.

A re-host mission to geosynchronous orbit or to a Lagrangian point would require the employment of launch vehicles that would permit the mission to arrive at, and to survive there. A spacecraft to a Lagrangian point location would likely involve a thermal design that was simpler than is used on Hubble since no eclipses would occur in that orbit. At geosynchronous orbit, eclipses occur twice a year, such as geosynchronous communications spacecraft experience. The relative absence of eclipses at geosynchronous or at a Lagrangian point would also allow a higher duty cycle for the acquisition of science data. Any new telescope located at either location would not be practical to service, a feature that has allowed the HST to be continually upgraded since launch.

Independent of the lack of solid technical (to say nothing of lack of schedule) information on re-host options, the committee had a number of important concerns with respect to the practical aspects of rehosting. In order to obtain science returns from the COS and the WFC3 comparable to the return from the instruments if they were flown on Hubble, the new satellite would have to carry a 2.4 meter diameter mirror, with diffraction-limited performance down to the ultraviolet (such a mirror diameter is especially necessary for the science of the WFC3 instrument), together with a very accurate pointing and guiding system that would be consistent with HST's capabilities. The two instruments would also have to be modified from their present states in order to be able to effectively use the new un-aberrated mirror that would likely be designed and built for the new spacecraft. (It seems inconceivable to me that an aberrated mirror would be purposefully designed for a brand new spacecraft just to match the Hubble's aberrated mirror.) In essence then, NASA would need to commit to, and to build and fly, a new Hubble telescope with an unaberrated mirror. The original Hubble development and testing program involved a lengthy and costly process. For mission success, this new re-host development program would require a commitment of very significant resources as well as political support over an interval of several years. The committee questioned whether such a commitment is likely to be given, let alone sustained in the face of numerous competing, high-priority, peer-reviewed astronomy programs that are already planned.

Even if the new Hubble program were adequately supported, such a program would come with the added risks that technical problems could halt or seriously delay development. In addition, as already noted in the Aerospace Corporation report, it was not clear to the committee that there would be significant cost savings over the options for a shuttle SM4 repair mission, particularly given the uncertainties of developing an entirely new satellite that performs like the original Hubble. Finally, unlike a Hubble repair, a satellite with re-hosted instruments would represent a significant new astronomy program that never was carefully evaluated for cost and schedule in the deliberative, detailed planning process that was carried out for astronomy research in the most recent Decadal Survey—a process that involved a great many resource and schedule trade-offs.

The SM4 Hubble service mission has been in NASA plans and budgeting profiles for years. In contrast, it would appear that any consideration of any re-hosting option would need to obtain and to critically evaluate accurate data on the costs for a satellite development mission of a complexity almost identical to that for the original Hubble. In addition, the review of a re-hosting mission by the astronomy community would have to establish its relative priority for funding and scheduling in terms of planned and on-going programs.

For these reasons, I personally would have strong reservations regarding a plan to re-host the COS and the WFC3 Hubble instruments on another satellite, particularly when compared to a shuttle repair mission. If a shuttle repair mission were not possible—if for instance NASA was not successful in returning shuttle to flight—then I would argue that the trade-offs of performing a re-hosting mission should be reviewed by the astronomy community in the context of its overall planning for space astronomy in the next decade.

In conclusion, I would like to reiterate the committee's conclusions that Hubble is a scientific asset of extraordinary value to the nation, and that shuttle servicing is the best option for extending the life of Hubble.

Thank you for the opportunity to appear before you today. I am prepared to answer any questions that you may have.

NEW REPORTS FROM THE SSB

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Science in NASA's Vision for Space Exploration

This report by the Committee on the Scientific Context for Space Exploration is available online at http://books.nap.edu/catalog/11225.html. The study was staffed by Joseph Alexander, Study Director, David Smith, Senior Staff Officer, Claudette Baylor-Fleming, Senior Project Assistant, and Cathy Gruber, Assistant Editor. The report summary is reproduced here without footnotes.

We live in an extraordinary period of exploration. Over the last few decades, humanity has used space as a vantage point from which to dramatically advance the exploration of our planet, the solar system, and the universe. In this transformative era, our understanding of every aspect of the cosmos has been reshaped as a result of a process driven by science—the desire to gain a fundamental and systematic understanding of the universe around us. Many aspects of exploration share this characteristic and constitute a form of science as well. This synergism establishes an overarching perspective from which to view science as an integral part of NASA's vision for space exploration.

On January 14, 2004, NASA received specific instructions from President George W. Bush to undertake a space exploration program with a clear set of goals, including implementation of "a sustained and affordable human and robotic program to explore the solar system and beyond." We have an opportunity, then, to pursue critical scientific questions that remain just beyond our grasp and to extend the human presence across the solar system and thus become a true space-faring civilization. The opportunities for future discovery are vast, encompassing our home planet Earth, the Moon and Mars and other places in the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond. Indeed, there is an extraordinary richness to the opportunities, but of course also a sobering reality, given the need to consider the limitations of available resources.

The issue thus is not what to pursue ultimately, but rather what to pursue first. Accordingly, the Committee on the Scientific Context for Space Exploration recommends the following *guiding principles*:

- Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.
- Both robotic spacecraft and human spaceflight should be used to fulfill scientific roles in NASA's mission to explore. When, where, and how they are used should depend on what best serves to advance intellectual understanding of the cosmos and our place in it and to lay the technical and cultural foundations for a space-faring civilization. Robotic exploration of space has produced and will continue to provide paradigm-altering discoveries; human spaceflight now presents a clear opportunity to change our sense of our place in the universe.
- The targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond.
- The targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what is our ultimate destiny.
- Preparation for long-duration human exploration missions should include research to resolve fundamental engineering and science challenges. More than simply development problems, those challenges are multifaceted and will require fundamental discoveries enabled by crosscutting research that spans traditional discipline boundaries.

The appropriate science in a vibrant space program is, therefore, nothing less than that science that will transform our understanding of the universe around us, and will in time transform us into a space-faring civilization that extends the human presence across the solar system.

NASA has embarked on a strategic planning activity that is built around 13 top-level agency objectives (see Chapter 2). The committee has reviewed the objectives, particularly those relating to science, and finds them to be comprehensive and appropriate. They have the potential to encompass all of the scientific topics that should be pursued under NASA's broad mission statement, which in turn is supported by the recent policy directives governing NASA. However, to be thorough and effective, strategic planning will require much forethought and the involvement of a diverse scientific community, because many of the scientific and technological challenges cut across several of the agency's objectives.

The breadth of NASA's top-level strategic objectives is an important strength. The topics do not distinguish between science and human exploration but rather reflect the recognition that each objective offers the opportunity both to advance and to benefit from understanding of the universe in which we live, and each is a worthy endeavor in a robust space exploration program. The committee believes that exploration, in the broad sense defined in this report, is the proper goal for NASA.

The committee recommends that, as planning roadmaps are developed to pursue NASA's objectives and as priorities are set among them, decisions be based on the potential for making the greatest impact and that the strategic roadmaps do the following:

- **Emphasize the critical scientific or technical breakthroughs that are possible, and in some cases necessary, and**
- **Highlight how a vibrant space program can be achieved by selecting from an array of approaches to realizing potential breakthroughs across the full spectrum of goals embodied in NASA's mission statement.**

For many years priorities for space science research have been developed and recommended through decadal surveys conducted under the auspices of the National Research Council (NRC). These studies use a consensus process to identify the most important, potentially revolutionary science that should be undertaken within the span of a decade, and numerous mission and program concepts that do not meet this standard are not pursued. In that sense NASA's science program currently is and always has been planned with the intent to generate the paradigm-altering science that NASA should undertake.

The committee considered how NRC science strategies and other reports can contribute to NASA's strategic planning process, and it makes the following recommendations:

- The most recent NRC decadal surveys for the fields of astronomy and astrophysics, solar system exploration, solar and space physics, and the interface between fundamental physics and cosmology do provide appropriate guidance regarding the science that is critical for the next decade of space exploration. **The committee recommends that these reports—*Astronomy and Astrophysics in the New Millennium* (2000), *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2002), *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2002), and *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (2003)—be used as the primary scientific starting points to guide the development of NASA's strategic roadmaps that include these areas.**
- Other highly relevant, discipline-specific NRC studies provide guidance for prioritizing critically important biomedical and microgravity research that must be conducted to enable human space exploration. **The committee recommends that these reports—*A Strategy for Research in Space Biology and Medicine in the New Century* (1998), *Safe Passage: Astronaut Care for Exploration Missions* (2001), *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences* (2002), *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies* (2000), and *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (2003)—be used as a starting point for setting priorities for research conducted on the International Space Station so that it directly supports future human exploration missions.**
- Science for enabling long-duration human spaceflight is inherently crosscutting, spans many of the agency's 13 new top-level objectives, and requires input from many fields of science and technology. Thus, no single decadal survey or combination of surveys necessarily can provide the totality of advice needed for the new programs that are anticipated under NASA's vision for exploration. Also, no single scientific or engineering discipline can provide the expertise and knowledge required for optimal solutions to the problems that will be encountered in human space exploration. Therefore, simply redoing the decadal surveys would not provide ideal guidance for defining the science that will enable human space exploration. Instead, the necessarily crosscutting advice should come from interdisciplinary groups of experts rather than from traditional committees that have a single scientific focus. **Therefore the committee recommends that NASA identify scientific and technical areas critical to enabling the human exploration program and that it move quickly to give those areas careful attention in a process that emphasizes crosscutting reviews to reflect their interdisciplinary scope, generates rigorous priority setting like that achieved in the decadal science surveys, and utilizes input from a broad range of expertise in the scientific and technical community.**
- NASA's robotic science program has enjoyed remarkable success, and it provides lessons that are worth applying to the human spaceflight program. **The committee recommends that successful aspects of the robotic science program—especially its emphasis on having a clear strategic plan that is executed so as to build on incremental successes to sustain momentum, use resources efficiently, enforce priorities, and enable future breakthroughs—should be applied in the human spaceflight program.**

New opportunities for research will arise as a result of human space exploration, and other research efforts will facilitate its success, but these two categories of science need to be treated differently. Science that is enabled by human exploration is properly competed directly with "decadal-survey" science and then ranked and prioritized according to the same rigorous criteria. For science to enable human exploration, competitive choices will depend on the criticality of the problem the science addresses and the likelihood that it will resolve the problem. For the former kind of science, understanding is an end in itself. For the latter, understanding is a means to the goal of resolving an identified problem, and the degree of understanding needed depends on the problem at hand.

The presidential policy directive on exploration also provides the context for deciding on the future of the space shuttle and the mission of the International Space Station. NASA is directed to retire the shuttle as soon as the assembly of the ISS is complete, which is assumed to be by 2010, and to focus the use of the ISS on supporting the goals of long-duration, human space exploration. Doing this in the most cost-effective way possible is essential for achieving NASA's goals for robotic and human exploration.

The Astrophysical Context of Life

This report by the Committee on the Origins and Evolution of Life will be available online late spring. The study was staffed by David Smith, Study Director, Robert L. Riemer, Senior Program Officer, Catherine A. Gruber, Assistant Editor, and Rodney Howard, Senior Project Assistant.

UNEDITED PREPUBLICATION DRAFT SUBJECT TO CORRECTION

Executive Summary

Background

The National Aeronautics and Space Administration (NASA) Astrobiology Roadmap summarizes astrobiology in the following way: "Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe." Astrobiology thus addresses three fundamental questions:

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

The Committee on the Origins and Evolution of Life was charged with investigating ways to augment and integrate the contributions of astronomy and astrophysics in astrobiology—in particular, in NASA's astrobiology program and in relevant programs in other federal agencies.

The goals set for this study were as follows:

- Identify areas where there can be especially fruitful collaborations between astrophysicists, biologists, biochemists, chemists, and planetary geologists.
- Define areas where astrophysics, biology, chemistry, and geology are ripe for mutually beneficial interchanges and define areas that are likely to remain independent for the near future.
- Suggest areas where current activities of the National Science Foundation (NSF) and other agencies might augment NASA programs.

In considering how to achieve these general goals, the committee focused on the key words in the statement of task (Appendix A): "to study the means to augment and integrate the activity of astronomy and astrophysics in the intellectual enterprise of astrobiology," in particular on the words "augment" and "integrate." It understood "augment" as an instruction to find issues in astronomical/astrobiological research where fruitful work could be done that is not now being done. The integration of interdisciplinary research topics is relevant to all the areas of astrobiology research, not just with respect to astronomy. The topic stimulated broad interest on the part of all the committee members and led to some generic—but, the committee believes, important—recommendations designed to facilitate interdisciplinary research.

The discussions about the charge led to the committee's specific approach to the study and to the structure of the report. Seven tasks were identified:

1. Outline current astronomical research relevant to astrobiology.
2. Define important areas that are relatively understudied and hence in need of more attention and support.
3. Address the means to integrate astrophysical research into the astrobiology enterprise.
4. Identify areas where there can be especially fruitful collaboration among astrophysicists, biologists, chemists, biochemists, planetary geologists, and planetary scientists that will serve the goals of astrobiological research.
5. Identify areas of astronomy that are likely to remain remote from the astrobiological enterprise.
6. Suggest areas where ongoing research sponsored by NSF, the Department of Energy (DOE), and the National Institutes of Health (NIH) can augment NASA support of astrobiological research and education in a manner that complements the astronomical interconnection with other disciplines.
7. Where applicable, point out the relevance to NASA missions.

Principal Conclusions

Astrophysical research is a vital part of astrobiology today, especially with the addition of the NASA Astrobiology Institute (NAI) nodes that are primarily focused on astrophysics. This report identifies still more areas where astrophysical research can contribute to astrobiology, including the galactic environment, cosmic irradiation in its myriad forms, bolide impacts, interstellar and circumstellar chemistry, prebiotic chemistry, and photosynthesis and molecular evolution in an astronomical context.

Astronomy brings two important perspectives to the study of astrobiology. One is to encourage thinking in a nonterracentric way. The opportunities are vast for different conditions to produce different outcomes for life, even within the standard paradigm of carbon-based life with a nucleotide-based coding system. The ambient conditions could be different—hotter, colder, more radiation or less—and the coding system could be different. It will be a challenge to discern the most important convergent processes when the details of overwhelmingly complex life are different. The other perspective that astronomy brings to astrobiology is that the astronomical environment—from the host star, to the ambient interstellar gas through which a planetary system passes in its galactic journey, to cosmic explosions—is intrinsically variable. The dominant driver of this variability is probably the host star, which is likely to be susceptible to violent chromospheric activity and nearly continuous flares when it is young or if its mass is less than that of the Sun, the most likely situation. Life in an intrinsically variable environment raises deep and interesting issues of fluctuating mutation rates, genetic variation processes, and the evolution of complexity—and even of evolvability itself. Some of these issues overlap with topics being pursued in biomedical research.

This study attempts to identify areas where astrophysical research can fruitfully interact with research in the other disciplines of astrobiology: biology, geology, and chemistry. It also identifies some broad issues involved in integrating astronomy within astrobiology. First, there is a need to recognize when astronomical research is relevant to astrobiology and when it is not. The consensus is that to be relevant to astrobiology, astronomical research should be "life-oriented." This is a broad and dynamic filter through which not all astronomical research will pass. Second, there is the need to integrate astrophysical research in the astrobiology effort. Here the report urges the NAI teams to develop metrics for determining when truly integrated interdisciplinary work involving astrophysics is being done and to actively promote that integration.

The third broad issue is that of integrating work in an intrinsically interdisciplinary field. While integrating astrophysics research is the focus, the problem transcends astronomy alone. To this end, the report recommends a series of educational and training initiatives conceived with the astronomy component of astrobiology in mind, but that could be applied to the whole enterprise. Among these initiatives are NAI's institutionalization of education and training, the establishment of an astrobiology graduate student fellowship program and of exchange programs for graduate students and sabbatical visitors, and sponsorship of a distinguished speaker series in astrobiology.

The astrophysics component of astrobiology has a rich and vibrant future in one of the great intellectual enterprises of humankind, understanding the origin and evolution of life.

FINDINGS AND RECOMMENDATIONS

The following is a summary of the committee's detailed findings and recommendations.

NASA Efforts in Astrophysics for Astrobiology

Funding for astrobiology is limited, and the boundaries of the field are unclear; there is a risk that some funds might go to research topics that cannot be justifiably classified as "astrobiology." The committee recommends that in funding decisions, NASA and other funding agencies should regard astronomical research as astrobiology if it is life-focused in plausible ways.

Review of current astronomically oriented research shows that it is concentrated in relatively few areas, especially in the Exobiology program. The committee recommends that NASA continue to ensure that an appropriate diversity of topics is included within the astrophysics component of astrobiology and that its support be coordinated with funding through other relevant programs. NASA also should develop metrics to evaluate the degree to which truly interdisciplinary work involving astronomy and astrophysics is being done in the current NAI nodes.

Areas That Could Benefit from Augmentation and Integration

Some broad areas are relatively understudied and would be especially amenable to focused effort in the near future: the galactic environment, the radiation/particle environment, bolide bombardment, interstellar molecules and their role in prebiotic chemistry, photochemistry and its relation to photosynthesis, and molecular evolution in an astronomical context. Specific areas needing attention by the research community and by funding agencies include the following:

- Galactic habitability, including correlating stellar heavy element abundance with the existence of planets; characterizing the interaction among stellar winds, the interstellar medium ram pressure, and the resulting cosmic ray flux; and determining which regions of the Galaxy could give rise to and sustain life.
- Characterization of the ultraviolet (UV), ionizing radiation, and particle flux incident on evolving, potentially life-hosting planets and moons.
- The variability of damaging UV and ionizing radiation over the course of life on Earth and how such conditions might be manifested on other life-hosting bodies.
- Planetary geology models to better understand the presence and nature of volcanism and tectonics on other planets as a function of the age of formation of the planet, the initial concentration of long-lived radioactive species, the accretion history, and the mass of the planet.
- Geological field work and models to characterize the rates of damage and mutation due to background radioactivities on evolving Earth and other potentially life-hosting bodies and to compare them with the rates due to other endogenous and exogenous radioactivities.
- Searches for cosmogenic material and other live radioactive elements in ice cores and ocean sediments.
- Research in the chemistry of the circumstellar accretion disks that evolve from molecular clouds, considering both gas- and solid-state phases and the delivery of chemical compounds to planet surfaces for an appropriate range of planets and planetary environments.
- Research to complete the interstellar and circumstellar molecular inventory and to test reaction pathways.
- Geological and geochemical work to identify ejecta material in the rock record surrounding large impact basins—in particular, to study existing evidence and search for additional signs of impact at the Permian/Triassic boundary and to document various anomalies in noble gas isotopic signatures and rare earth and other metal abundances that can be clearly linked to extraterrestrial impactors.
- Return to the Moon to acquire more lunar samples to help determine when the "impact frustration" of life's origin ended by sampling more sites—particularly sites that are older than the six sites sampled by the Apollo astronauts and the three sites sampled by the Russian robotic sample-return missions and, especially, the oldest and largest impact basin on the Moon, the South Pole-Aitken Basin.
- Research on how carbon, nitrogen, and sulfur cycles might work on a prebiotic planet with an ocean and an incident flux of

photons and particles, and how these cycles might couple with primitive life forms to provide feedstocks for their formation and energy for their metabolism.

- Coordinated theoretical, laboratory, and observational studies of interstellar chemistry, accretion, condensation, and transport processes to determine the inventory of compounds that was delivered to a young planet, when they were available, where they were available, and in what quantities.
- Studies of abiotic photochemistry in concert with astronomical sources of trace elements and energy to determine whether trace elements play a role in photochemical sources of organic compounds and/or high-energy activated compounds.
- Studies of the extent to which the astrophysical environment could have fostered symmetry breaking in prebiotic organic pools.
- Studies to understand the evolution of earthlike organisms and organisms with other coding mechanisms that are subjected to the fluctuating thermal and radiation environments expected for planetary systems with various impact histories and planets orbiting stars of various masses and ages in different parts of the Galaxy.
- In vitro and in silico studies to learn how the stochastic variability of the environment, including the mutational environment, affects the evolution of life, especially by promoting complexity and the evolution of evolvability.

Integrating Astronomy with the Other Disciplines of Astrobiology

The committee identified three factors that currently limit the integration of astronomy and astrophysics with astrobiology and, indeed, limit robust interdisciplinary research of any kind: (1) a lack of common goals and interests, (2) lack of a common language, and (3) insufficient background in allied fields to allow experts to do useful interdisciplinary work.

The committee recommends to NASA, other funding agencies, and the research community the following approaches to overcoming communication barriers:

- Continue and expand cross-disciplinary discussions on the origin and evolution of life on Earth and elsewhere, as are already being promoted by the NAI.
- Continue intellectual exchange through interdisciplinary meetings, focus groups, a speaker program, and workshops, all targeted at augmenting and integrating astronomy and astrophysics with other astrobiology subdisciplines.
- Promote a professional society (and cross-disciplinary branches within existing societies) that will cover the full range of disciplines that make up astrobiology, from astronomy to geosciences to biology. The International Society for the Study of the Origins of Life, which holds triennial meetings, may provide an appropriate basis for this. The BioAstronomy conferences sponsored by the International Astronomical Union, the astrobiology conferences held at NASA Ames Research Center, and the Gordon Research Conferences on the Origin of Life are useful but do not fulfill the needed roles of a professional society.
- Undertake missions to asteroids, comets, moons such as Titan, and, possibly, Saturn's rings to sample and analyze the surface organic chemistry.
- Broaden the definition of outreach activities within the NAI beyond general public awareness and K-12 education to achieve the greater degree of cross-fertilization that is needed among NAI senior researchers, postdoctoral fellows, and students.
- Reach out to university faculty in general, not just to NAI members and affiliates. This is essential for astrobiology to be embraced as a discipline and for extending and perpetuating support beyond NAI/NASA, which is otherwise unlikely to happen.

Education at all levels is a central issue. The committee recommends multiple approaches that invest both in training the next generation and in giving the larger scientific community opportunities for interdisciplinary training and collaboration.

- NASA should encourage NAI teams to institutionalize education in astrobiology. In particular, the committee recommends that the next competition for NAI centers encourage the creation of academic programs for interdisciplinary undergraduate and graduate training in astrobiology.
- In order to provide opportunities for graduate training within and outside the NAI centers, NASA should establish an astrobiology graduate student fellowship program similar to existing programs in space and Earth science. These fellowships should be open to students enrolled in any accredited graduate program within the United States.
- NASA should encourage the NAI to foster cross- and interdisciplinary training opportunities for graduate students and faculty, as already exist for postdoctoral fellows. In particular, the committee recommends that exchange programs be created to allow students to matriculate in programs outside their home field and that resources be made available for a sabbatical program for the interdisciplinary training of established scientists.
- NASA should encourage NAI teams and NASA Specialized Center of Research and Training (NSCORT) nodes to engage in a self-study as part of their reporting processes to assess the progress of graduate and postdoctoral programs in training truly interdisciplinary scientists who actively engage in interdisciplinary research.
- The NAI should sponsor a distinguished speaker series in astrobiology. It would identify accomplished speakers and provide travel support for them to present their interdisciplinary research at universities and colleges. Speakers should be selected on the basis of both disciplinary and demographic diversity. The institutions hosting the speakers would be required to involve multiple academic departments or programs.

Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision

On February 11, 2005, Committee Chair C. Megan Urry sent a letter report to NASA Associate Administrator for Science, Science Mission Directorate, Alphonso V. Diaz, and Michael S. Turner, Assistant Director, Mathematical and Physical Sciences, National Science Foundation. The letter report is available in its entirety online at http://books.nap.edu/catalog/11230.html. The study was staffed by Brian D. Dewhurst, Study Director, and Celeste Naylor, Senior Project Assistant.

A condensed version of the letter report follows.

The Committee to Assess Progress Toward the Decadal Vision in Astronomy and Astrophysics provided its letter report to NASA and NSF on February 11, 2005. The purpose of the report was to review the scientific discoveries and technical advances in astronomy and astrophysics over the 5 years since the publication of the 2000 decadal survey, *Astronomy and Astrophysics in the New Millennium*, and the 2003 report, *Connecting Quarks with the Cosmos*. The report also was intended to address the implications of scientific and technical developments as well as changes in the federal program and to consider whether the overall science strategy laid out in the two prior reports is on course or should be reexamined.

Highlights of the committee's conclusions and recommendations include the following:

- The remarkable advances in understanding in astronomy and astrophysics achieved over the past 5 years do not require that the NRC reexamine the decadal survey report or undertake an in-depth mid-course review of the scientific goals or recommended priorities.
- The suite of projects recommended in the decadal survey report provides the flexibility to explore the universe across a wide range of conditions. A broad portfolio of activities is a powerful tool for exploration.
- The formation of the federal Astronomy and Astrophysics Advisory Committee (AAAC) and recent interagency coordination efforts (e.g., as embodied in the Office of Science and Technology Policy Inter-agency Working Group on the Physics of the Universe) represent significant and important programmatic advances that aid the fulfillment of the decadal vision.
- Future planning for astronomy and astrophysics should take into account the increasing involvement of the DOE's Office of Science and the scientists that it supports.
- The NASA Beyond Einstein roadmap (currently being updated), is an excellent implementation and synthesis of the decadal survey report and *Connecting Quarks with the Cosmos*. For the program to fulfill its promise, support for the Beyond Einstein projects needs to be sustained.
- Although the decadal survey report assumed that the Hubble Space Telescope (HST) would be kept operating until 2010, it is the judgment of the committee that the survey report's recommended priorities should form the basis of the nation's program in astronomy and astrophysics even if HST ceases operation.
- The committee believes that maintaining the breadth of the astronomy and astrophysics enterprise at NASA is consistent with the new vision for space exploration.
- The committee and the community it represents value immensely the ongoing dialog between the astronomy and astrophysics community and the agencies.

FROM OUR STAFF

Dr. Tamara L. Dickinson has joined the SSB staff as the Associate Director. Tammy comes to us from the NRC Board on Earth Sciences and Resources where she served for 8 years as study director of the Committee on Earth Resources. Prior to her work at the NRC, she served as program director for the Petrology and Geochemistry Program in the Division of Earth Sciences at the National Science Foundation and as the discipline scientist for the Planetary Materials and Geochemistry Program at NASA Headquarters. As a post-doctoral fellow at the NASA Johnson Space Center, she conducted experiments on the origin and evolution of lunar rocks and highly reduced igneous meteorites. She holds a Ph.D. and an M.S. in geology from the University of New Mexico and a B.A. in geology from the University of Northern Iowa.

Dr. Dwayne A. Day is the new Space Studies Board Research Associate. Day has a Ph.D. in Political Science from The George Washington University and has previously worked for the Columbia Accident Investigation Board and the Congressional Budget Office. He is associate editor of Raumfahrt Concret, a German spaceflight magazine, and frequently writes for such publications as Spaceflight, Air Force magazine, and Novosti Kosmonavtiki ("Cosmonautics News"). He edited *Eye in the Sky*, a history of the early American satellite reconnaissance program, and wrote *Lightning Rod*, a history of the Air Force Chief Scientist's Office.

Staff Officer David Smith in collaboration with other SSB staff members completed review of applications for the SSB Summer 2005 Undergraduate Internship Program. Congratulations to the selected candidate, ***Matthew Broughton***, a budding space physicist from Augsburg College.

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2005		
APRIL		
5-7	COMMITTEE TO REVIEW THE SCIENCE REQUIREMENTS FOR THE ATACAMA LARGE MILLIMETER ARRAY (ALMA)	STANFORD, CA
18-20	COMMITTEE ON PLANETARY AND LUNAR EXPLORATION	WASHINGTON, DC
MAY		
9-10	EARTH SCIENCE AND APPLICATIONS FROM SPACE: PANEL ON WATER RESOURCES & GLOBAL HYDROLOGIC CYCLE	BOULDER, CO
16-18	ROADMAPS -- SCIENCE PANEL	WASHINGTON, DC
19-20	COMMITTEE ON ASTRONOMY AND ASTROPHYSICS	WASHINGTON, DC
31-**June 2**	COMMITTEE ON THE ORIGINS AND EVOLUTION OF LIFE	WOODS HOLE, MA
JUNE		
7-9	SPACE STUDIES BOARD @JET PROPULSION LABORATORY	PASADENA, CA
13-15	ROADMAPS -- SCIENCE PANEL	WASHINGTON, DC
15-17	ROADMAPS -- ISS PANEL	WASHINGTON, DC
22-23	EARTH SCIENCE AND APPLICATIONS FROM SPACE: WEATHER PANEL (TENTATIVE)	BOULDER, CO
JULY		
20-22	COMMITTEE ON PLANETARY AND LUNAR EXPLORATION @ WESLEYAN UNIV.	MIDDLETOWN, CT
AUGUST		
9-11	SSB EXECUTIVE COMMITTEE MEETING	WOODS HOLE, MA
29-**SEPT. 1**	EARTH SCIENCE AND APPLICATIONS FROM SPACE: COMMITTEE & PANELS	IRVINE, CA
OCTOBER	COMMITTEE ON SOLAR AND SPACE PHYSICS: WORKSHOP ON RADIATION ENVIRONMENT IN THE SOLAR SYSTEM (TENTATIVE)	TBD
NOVEMBER		
2-4	COMMITTEE ON PLANETARY AND LUNAR EXPLORATION	IRVINE, CA
8-10	SPACE STUDIES BOARD	IRVINE, CA
29-30	COMMITTEE ON ASTRONOMY AND ASTROPHYSICS	IRVINE, CA

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___ Utilization of Operational Environmental Satellite Data

___ Understanding the Sun and Solar System Plasmas—a 40-page full color booklet based on the report The Sun to Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics

___ Exploration of the Outer Heliosphere and the Local Interstellar Medium—A Workshop Report

___ Solar and Space Physics and Its Role in Space Exploration

___ Plasma Physics in the Local Cosmos

___ Space Studies Board Annual Report 2003

___ Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy
__ Paper __ 2MB PDF (Be sure to include email address in shipping information section above.)

___ New Frontiers in Solar System Exploration – a 32-page full color booklet based on the SSB report New Frontiers in the Solar System: An Integrated Exploration Strategy.

___ The Sun to the Earth—and Beyond: Panel Reports

___ Assessment of NASA's Draft 2003 Space Science Enterprise Strategy, a letter report, May 29, 2003

___ Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations

___ Using Remote Sensing in State and Local Government: Information for Management and Decision Making

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___ Space Studies Board Annual Report 2002

___ Assessment of Directions in Microgravity and Physical Sciences Research at NASA **(CD only.)**

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___ Space Studies Board Annual Report 2001

___ The Quarantine and Certification of Martian Samples

___ Issues in the Integration of Research and Operational Satellites for Climate Research: I. Science and Design

___ Issues in the Integration of Research and Operational Satellite Systems for Climate Research II. Implementation

___ Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies

___ Review of NASA's Biomedical Research Program

___ Institutional Arrangements for Space Station Research

___ Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making

___ Ground-based Solar Research: An Assessment and Strategy for the Future **(Limited Supply.)**

___ A Strategy for Research in Space Biology and Medicine in the New Century

___ Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis

___ U.S.-European Collaboration in Space Science

Farewell to the SSB Administrative Officer….

After fifteen years of service with the Space Studies Board (SSB), we bid farewell to Betty C. Guyot, SSB Administrative Officer. On April 29, 2005, Betty will move on to follow her dreams, and enjoy life's greatest pleasures beyond the SSB. During her fifteen years at the SSB, Betty has pioneered numerous projects that include the SSB Operating Plan, Annual Report and Newsletter. Her dedication to the production of these reports has been invaluable. Her unyielding efforts with the SSB proposals and budgets made the process less stressful, ensuring that each contract was signed, sealed and delivered to the sponsor on time without hesitation. Her guidance of the SSB Project Assistants' Group has been exceptionally brilliant. While we are sad to see her leave, we bid Betty a fond farewell and wish her much happiness in all her future endeavors.

A QUARTERLY NEWSLETTER OF THE SPACE STUDIES BOARD

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