Free Executive Summary

NASA's Beyond Einstein Program: An Architecture for Implementation

Committee on NASA's Einstein Program: An Architecture for Implementation, National Research Council

ISBN: 978-0-309-11162-1, 220 pages, 8 1/2 x 11, paperback (2007)

Executive Summary

BACKGROUND

"Beyond Einstein" science is a term that applies to a set of new scientific challenges at the intersection of physics and astrophysics. Observations of the cosmos now have the potential to extend our basic physical laws beyond where 20th century research left them. Such observations can provide stringent new tests of Einstein's general theory of relativity, indicate how to extend the standard model of elementary particle physics, and—if direct measurements of gravitational waves were made—give astrophysics an entirely new way of observing the universe. New physical understanding may be required to explain cosmological observations, and the challenge of investigating the laws of physics using astronomical techniques promises to bring higher precision, clarity, and completeness to many astrophysical investigations relating to galaxies, black holes, and the large-scale structure of the universe, among other areas.

In 2003, NASA, working with the astronomy and astrophysics communities, prepared a research roadmap entitled *Beyond Einstein: From the Big Bang to Black Holes*.[1] This roadmap proposed that NASA undertake space missions in five areas in order to study dark energy, black holes, gravitational radiation, and the inflation of the early universe, and to test Einstein's theory of gravitation. Two of the five mission areas were Einstein Great Observatories: Constellation-X (Con-X) and the Laser Interferometer Space Antenna (LISA). The other three were planned as smaller Einstein Probes: Inflation Probe (IP), the Joint Dark Energy Mission (JDEM), and Black Hole Finder Probe (BHFP). Candidates for all of these missions are currently in various stages of definition and development.

Prompted by Congressional language inserted in the formulation of the FY 2007 budget, NASA and DOE asked the NRC to prepare a report reviewing NASA's Beyond Einstein program. The report was to assess the five Beyond Einstein missions and recommend one mission for first development and

[1] National Aeronautics and Space Administration, *Beyond Einstein: From the Big Bang to Black Holes*, Washington, D.C., January 2003. This document was part of NASA's 2003 GPRA roadmapping effort.

launch utilizing a Beyond Einstein program funding wedge[2] that will start in 2009. To accomplish this, the committee assessed all five mission areas using criteria that address both potential scientific impact and technical readiness. In addition, the report was to assess each mission in sufficient detail to provide input for decisions by NASA and for the next Astronomy and Astrophysics Decadal Survey regarding both the ordering of the remaining missions and the investment strategy for future technology development within the Beyond Einstein Program. In responding to this latter charge, the committee has attempted to indicate what next steps each of the missions would need to take in order to prepare for future assessments.

MISSION ASSESSMENTS

The criteria utilized by the committee in assessing the missions fell into two general categories. First, the committee looked at the potential scientific impact within the context of other existing and planned space-based and ground-based missions. Here the committee considered how directly the mission would address the research goals of the Beyond Einstein research program, likely contributions to the broader field of astrophysics, the potential for revolutionary scientific discovery, the scientific risks and readiness of the mission, and its competition from other ground and space-based instruments.

Second, the committee considered the realism of preliminary technology and management plans and of cost estimates. Criteria used by the committee included plans for the maturity of critical mission technology, technical performance margins, schedule margins, risk mitigation plans, and estimated costs versus independent probable cost estimates.

The committee made its recommendations based on the above criteria, but during its deliberations identified several policy related issues relevant to the Beyond Einstein program. These issues included: implications for U.S. science and technology leadership, program funding constraints, relations in inter-agency and international partnerships, investments in underlying research and technology and supporting infrastructure, and impact of International Traffic in Arms Regulations (ITAR). The committee reviewed these issues in order to understand the broader context of the report.

The committee performed extensive assessments for each mission utilizing the above criteria, and it is impossible to adequately summarize here all of the points that factored into the final mission selection. Rather, each of the missions reviewed by the committee is briefly described below, along with a summary of a few of the major points from the committee's assessment.

Science Impact and Technology Readiness

Black Hole Finder Probe

The two Black Hole Finder Probe (BHFP) mission concepts presented to the committee are called EXIST (Energetic X-ray Imaging Survey Telescope) and CASTER (Coded Aperture Survey Telescope for Energetic Radiation). These two telescopes both utilize wide-field coded-aperture hard X-ray telescopes, divided into arrays of sub-telescopes at two different energy bands. With their arrays of sub-telescopes, either would survey the entire sky between a few keV and 600 keV during the course of their 95-minute orbits, providing information about source variability on time scales ranging from milliseconds to many days.

[2] NASA's FY 2007 budget request projected NASA's level of support for Beyond Einstein missions covering the years FY2007-2011. This projection begins to increase significantly in FY 2009 and continues to increase through FY 2010 and FY 2011. The projected increase is identified in the report as the "Beyond Einstein wedge."

Science Importance and Readiness

BHFP is designed to find black holes on all scales, from one to billions of solar masses. It will observe high-energy x-ray emission from accreting black holes and explosive transients and address the question of how black holes form and grow.

The BHFP will be unique among current or planned missions in high-energy x-ray sensitivity combined with large field of view and frequent coverage of the sky. The resulting hard x-ray sky maps, temporal variability data, and the large number of short-lived transient detections will have direct impact on a number of important astrophysical questions. BHFP will be a unique window into the properties and evolution of astronomical objects whose physics is dominated by strong gravity.

The committee found the science risk for BHFP mission candidates to be rather high. Although a census of massive black holes in galaxies can be achieved, only very high-luminosity and high mass black holes will be seen at high redshifts. In addition, the very uncertain conversion from x-ray luminosity to black-hole growth rate implies that BHFP will not provide a unique value (to better than a factor of 10) of the black hole growth rate (e.g., in solar masses per year) in any individual galaxy or even in the entire Universe. Finally, the difficulty in identifying host galaxies also yields significant risk in the interpretation of BHFP results. Both multi-wavelength observational data and theoretical advances (e.g., in black hole accretion modeling) will be necessary for BHFP to realize its full scientific potential.

Technology Readiness

The two BHFP mission candidates differ primarily in their selection of detector material. CASTER faces more technology maturity challenges as the detector technology in general is at lower technology readiness levels (TRL's) than that of EXIST, as discussed in Chapter 3. The estimated costs for both mission concepts are higher than originally envisioned. In the original Beyond Einstein Roadmap, the Einstein probes were envisioned as medium-scale missions that could be executed much more rapidly and cheaply than the flagship LISA and Constellation-X missions. However, the BHFP probe concepts now have costs estimated by the projects in the vicinity of a billion dollars. This report's independent assessment (Chapter 3) also finds probable costs inconsistent with the original Einstein Probe cost range. The committee suggests that judicious tradeoffs among sensitivity, detector area and observing time may enable a smaller telescope to carry out the most important BHFP science at lower cost.

Constellation-X

The Constellation-X mission has been designed to be a general-purpose astrophysical observatory. Its primary new capability is very high spectral resolution, high throughput x-ray spectroscopy, representing an increase in these capabilities of roughly two orders of magnitude over missions currently flying.

Science Importance and Readiness

Con-X will make the broadest and most diverse contributions to astronomy of any of the candidate Beyond Einstein missions. The committee understands that it has the potential to make strong contributions to Beyond Einstein science through the study of the evolution of supermassive black holes and mapping of the dynamics of clusters of galaxies. However, other BE missions will address both the measurement of dark energy parameters and tests of strong-field General Relativity in a more focused and definitive manner and, as a result, the committee did not choose Con-X as one of the highest priorities for BE funding. The committee concluded that the merits of Con-X can only be fully assessed when it is judged as a major astrophysics mission in a context broader than that of the Beyond Einstein program. Given that Con-X was ranked second only to the James Webb Space Telescope in the 2001 *Decadal*

Survey[3], NASA's characterization of it as a Beyond Einstein Mission understates its significance to general astronomy.

Technology Readiness

Con-X is one of the best studied and tested of the missions presented to the panel. Aside from the well-known risks of satellite implementation, there are a number of technical risks that have been called out by the Con-X team and also discussed in Chapter 3. Chief among these include achieving the needed mirror angular resolution and the development of the position-sensitive micro-calorimeters. The Con-X Project has reasonable plans to mature both of these technologies, and, given adequate resources and time, there is little reason to expect that they will limit the main science goals of the observatory.

Con-X development activities need to continue aggressively in areas such as achieving the mirror angular resolution, cooling technology and x-ray micro-calorimeter arrays to improve the Con-X mission's readiness for the next Astronomy and Astrophysics Decadal Survey. The committee, however, does not believe that the current Beyond Einstein wedge should fund these activities. Beyond Einstein is not the sole justification for Con-X as its primary science capabilities support a much broader research program.

Inflation Probe

The Inflation Probe (IP) mission area seeks to study for the first time the conditions that existed during the crucial phase of exponential expansion in the early history of the universe. Four IP mission concepts have been proposed to date. Three propose to study the signal impressed on the polarization of the Cosmic Microwave Background (CMB) radiation by gravity waves induced during the inflationary period. The fourth proposes to measure the structure in the universe on various length scales, arising from the primordial density fluctuations induced by inflation.

Science Importance and Readiness

Understanding inflation is an important Beyond Einstein program goal. The exponential expansion during the era of inflation may have similarities with the much more slowly accelerating expansion occurring today that is attributed to the presence of dark energy. A deeper understanding of both inflation and dark energy is needed to explore that similarity. Studying inflation may also lead to understanding the source of the largest structures in the Universe, which appear to be linked to quantum fluctuations and phenomena at the smallest scales. The theoretical framework for understanding the results of both the CMB and high-redshift galaxy observations is already in place.

Technology Readiness

One of the four mission concepts, the Cosmic Inflation Probe (CIP), has a mission design that is a modification of existing missions. Although the state of CIP technology is more advanced than the polarization missions, it would benefit from advances in grating technologies. NASA's Astrophysics Research Grants Program is already in place to fund these types of investigations. However, it should be noted that the scope of this program may need to be changed to accommodate aggressive IP development.

The three CMB polarization Inflation Probes collectively are in an earlier stage of development than CIP. The three CMB proposals outline detector and instrument concepts that are extrapolations from existing experiments. The CMB polarization experiments EPIC-F, EPIC-I, and CMBPol all require extremely sensitive millimeter wave continuum detectors, and extremely effective rejection of the common mode noise from the anisotropy signal. All three of these missions have proposed to use state-of-the-art detectors to reach the required high sensitivity. If the European Planck mission is successful it will go a large part of the way, but not the entire way, toward proving the readiness of the detector technology. Along with continued grating technology investment required to continue to mature CIP, significant

[3] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

continued support of detector and ultra-cool cryo-coolers (sub 100 mK) is needed to push the three polarization missions along. Given their state of development, it is not necessary to provide direct technology development support to each of the mission teams. Although the state of CIP technology is more advanced than the polarization missions, CIP would benefit from intensive theoretical investigations as well as further refinement of grating technologies.

JDEM

The Joint Dark Energy Mission (JDEM) is a partner mission between NASA and the Department of Energy that would use an optical-to-near-infrared wide field survey telescope to investigate the distribution of dark energy. Three concepts for a JDEM mission have thus far been proposed: the Supernova Acceleration Probe (SNAP), the Dark Energy Space Telescope (DESTINY), and the Advanced Dark Energy Physics Telescope (ADEPT).

Science Importance and Readiness

Understanding the nature of dark energy is one of the most important scientific endeavors of our era. A central goal of JDEM is a precision measurement of the expansion history of the universe to determine whether the contribution of dark energy to the expansion rate varies with time. A discovery that the expansion history is not consistent with Einstein's cosmological constant would have a fundamental impact on physics and astronomy.

JDEM will significantly advance both dark energy and general astrophysical research. The wide field optical and near infrared surveys required for dark energy studies will create large, rich data sets useful for many other astrophysics studies, enlarging an already significant discovery potential. A full-sky, near infrared spectroscopic survey, such as ADEPT proposes, has never been performed, and no comparable mission is planned. This survey would open the emission-line universe, providing new probes of star formation during the epoch when galaxies grow, along with data for many other astrophysics studies. A low background, wide field imaging survey, such as DESTINY and SNAP propose, would provide a much larger diffraction-limited NIR survey than otherwise available. Such a survey would revolutionize our understanding of how and when galaxies acquire their mass, as well as provide copious data for many other astrophysics studies.

The principal JDEM science risk, common to many dark energy studies, arises from the need to control systematic uncertainties sufficiently to achieve significantly improved precision. Space measurements have the potential to control observational uncertainties better than ground techniques, but the space techniques have not yet been demonstrated to the required levels. External systematic uncertainties of an astrophysical nature could conceivably prove irreducible during the mission lifetime. JDEM will try to mitigate both types of risk by employing multiple complementary observational techniques and by collecting rich datasets. Cross-checking with large statistically significant data sets should help sort out systematic trends in the data.

Technology Readiness

As described in Chapter 3, two of the three candidate missions for JDEM, Destiny and SNAP, are relatively mature since most of their critical technologies are at levels 5-6 or higher. (The SNAP CCD's are an exception at TRL level 4-5, but there is a good plan to bring them to flight readiness.) ADEPT did not provide the committee with adequate data to evaluate readiness, but in general their critical technology has flight heritage and no major challenges.

LISA

The proposed Laser Interferometer Space Antenna (LISA) is a gravitational-wave antenna. At the low frequencies where a rich variety of strong signals is expected to exist, gravity waves can only be detected from space. LISA will consist of an array of three spacecraft orbiting the sun, each separated from its neighbor by about 5 million kilometers. Laser beams will be used to measure the minute changes in distance between the spacecraft induced by passing gravitational waves.

Science Importance and Readiness

LISA promises to open a completely new window into the heart of the most energetic processes in the universe, with consequences fundamental to both physics and astronomy. During its proposed five-year mission, LISA expects to detect gravitational waves from the merger of massive black holes in the centers of galaxies or stellar clusters at cosmological distances, and from stellar mass compact objects as they orbit and fall into massive black holes. Studying these waves will allow researchers to trace the history of the growth of massive holes and the formation of galactic structure, to test general relativity in the strong-field dynamical regime, and to determine if the black holes of nature are truly described by the geometry predicted in Einstein's theory. LISA will measure the signals from close binaries of white dwarfs, neutron stars, or stellar mass black holes in the Milky Way and nearby galaxies. This will permit a census of compact binary objects throughout the Galaxy. There may also be waves from exotic or unexpected sources, such as cosmological backgrounds, cosmic string kinks, or boson stars. LISA will also be able to measure the speed of gravitational waves to very high precision, may study whether there are more than the two polarizations predicted by general relativity, and will be able to measure absolute distances to far-away objects.

Technology Readiness

LISA has had considerable technology development since entering Phase A development in 2004, and has had a baseline mission architecture in place for some time. Nevertheless a number of critical technologies and performance requirements must be developed and verified before LISA is technically ready to move into the implementation phase. Some critical technologies will be tested on the ESA-NASA LISA Pathfinder scheduled for launch in October 2009. Success of the Pathfinder is a prerequisite for LISA to proceed with implementation.

Not all of the critical LISA technologies and performance will be tested on the Pathfinder. Therefore given the scientific importance of LISA, the committee strongly believes that a high priority for NASA's Beyond Einstein program is to accelerate the maturation of those remaining LISA technologies not tested on Pathfinder. Candidates for this funding include: micro-Newton thruster technology development and lifetime tests; Point-Ahead Actuator; Phase Measurement System; and Laser Frequency Noise Suppression. As discussed in the report, these were assessed to be at TRL levels of 4 or less.

Cost Realism

The committee was also asked to evaluate the cost realism of the candidate Beyond Einstein mission set. The committee worked with an experienced outside contractor to develop independent cost estimates and a probable cost range for each mission. The probable cost ranges were also compared to those of previous missions of similar scope and complexity. In all cases, the committee's assessment indicates higher costs and longer schedules than those estimated by the mission teams. This is typical of the differences between the estimates developed by mission teams and by independent cost estimators at this stage of a program. Given the long history of missions comparable to the BE mission candidates, the committee does believe that the most realistic cost range for each of these missions is significantly more than the current team estimates.

The committee also compared its most probable funding profiles with NASA's projected Beyond Einstein budget wedge. This analysis showed that the funding wedge alone is inadequate to develop any candidate Beyond Einstein mission on its nominal schedule. However, the committee used this data to indicate how the JDEM and LISA development and funding profiles could be adjusted to fit within

NASA's wedge, given that DOE expects to co-fund JDEM up to approximately $400M[4] and ESA plans approximately $500M for LISA[5].

MAJOR FINDINGS AND RECOMMENDATIONS

In light of the considerations summarized above, and described in considerably more detail in the body of the report, the committee has the following major findings and principal recommendations. The findings are not listed in order of priority, but rather in a sequence that conveys the committee's reasoning.

Finding 1. The Beyond Einstein scientific issues are so compelling that research in this area will be pursued for many years to come. All five mission areas in NASA's Beyond Einstein plan address key questions that take physics and astronomy beyond where the century of Einstein left them.

Finding 2. The Constellation-X mission will make the broadest and most diverse contributions to astronomy of any of the candidate Beyond Einstein missions. While it can make strong contributions to Beyond Einstein science, other BE missions address the measurement of dark energy parameters and tests of strong-field General Relativity in a more focused and definitive manner.

Finding 3. Two mission areas stand out for the directness with which they address Beyond Einstein goals and their potential for broader scientific impact: LISA and JDEM.

Finding 4. LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals.

Finding 5. The ESA-NASA LISA Pathfinder mission that is scheduled for launch in late 2009 will assess the operation of several critical LISA technologies in space. The committee believes it is more responsible technically and financially to propose a LISA new start after the Pathfinder results are taken into account. In addition, Pathfinder will not test all technologies critical to LISA. Thus, it would be prudent for NASA to invest further in LISA technology development and risk reduction, to help ensure that NASA is in a position to proceed with ESA to a formal new start as soon as possible after the LISA Pathfinder results are understood.

Finding 6. A JDEM mission will set the standard in the precision of its determination of the distribution of dark energy in the distant universe. By clarifying the properties of 70 percent of the mass-energy in the universe, JDEM's potential for fundamental advancement of both astronomy and physics is substantial. A JDEM mission will also bring important benefits to general astronomy. In particular, JDEM will provide highly detailed information for understanding how galaxies form and acquire their mass.

Finding 7. The JDEM mission candidates identified thus far are based on instrument and spacecraft technologies that have either been flown in space or have been extensively developed in

---

[4]Turner, Kathy. Program Manager, Office of High Energy Physics at DOE. "Note to BEPAC Regarding DOE's JDEM Plans." E-mail communication March 30, 2007.
[5] European Space Agency LISA budget data provided to the Committee by David Southwood, Director of Science in discussions on ESA's Astrophysics and Fundamental Physics program, April 5, 2007.

other programs. A JDEM mission selected in 2009 could proceed smoothly to a timely and successful launch.

Finding 8. The present NASA Beyond Einstein funding wedge alone is inadequate to develop any candidate Beyond Einstein mission on its nominal schedule. However, both JDEM and LISA could be carried out with the currently forecasted NASA contribution if DOE's contribution that benefits JDEM is taken into account and if LISA's development schedule is extended and funding from ESA is assumed.

Recommendation 1. ***NASA and DOE should proceed immediately with a competition to select a Joint Dark Energy Mission for a 2009 new start. The broad mission goals in the Request for Proposal should be (1) to determine the properties of dark energy with high precision and (2) to enable a broad range of astronomical investigations. The committee encourages the Agencies to seek as wide a variety of mission concepts and partnerships as possible.***

Recommendation 2. ***NASA should invest additional Beyond Einstein funds in LISA technology development and risk reduction, to help ensure that the Agency is in a position to proceed in partnership with ESA to a new start after the LISA Pathfinder results are understood.***

Recommendation 3. ***NASA should move forward with appropriate measures to increase the readiness of the three remaining mission areas—Black Hole Finder Probe, Constellation-X, and Inflation Probe—for consideration by NASA and the NRC Decadal Survey of Astronomy and Astrophysics.***

The committee strongly believes that future technology investment is required and warranted in all of the Beyond Einstein mission areas. The candidates for JDEM, the committee's first priority mission area, need continued funding until NASA and DOE conduct a competition and selection for a JDEM. Furthermore, the committee believes that the competition to select a JDEM should be open to other mission concepts, launch opportunities, measurement techniques, and international partnerships. The next highest priority for funding from the current 2009 Beyond Einstein NASA budget wedge is to accelerate the maturation of those mission critical LISA technologies that are currently at low technology readiness levels. This funding will be needed until and if NASA initiates a post-Pathfinder mission start for LISA.

The current Beyond Einstein budget profile will not support technology development beyond JDEM and LISA. The committee did not develop a priority order for the remaining mission areas and believes all their component missions require additional technology maturity before they can be fully evaluated. Their technology development should continue to be supported in the broader astrophysics program, at least at a level that allows a sound appraisal by the next Astronomy and Astrophysics Decadal Survey.

PREPUBLICATION COPY
Subject to Further Editorial Correction

NASA's Beyond Einstein Program: An Architecture for Implementation

Committee on NASA's Beyond Einstein Program: An Architecture for Implementation
Space Studies Board
and
Board on Physics and Astronomy
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study is based on work supported by the Contract NASW-010001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number 13: 978-0-309-0XXXX-X
International Standard Book Number 10: 0-XXX-0XXXX-X

Cover:

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Other Reports of the Space Studies Board

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (2007)
Exploring Organic Environments in the Solar System (SSB with the Board on Chemical Sciences and Technology, 2007)
A Performance Assessment of NASA's Astrophysics Program (SSB with the Board on Physics and Astronomy, 2007)

An Assessment of Balance in NASA's Science Programs (2006)
Assessment of NASA's Mars Architecture 2007-2016 (2006)
Assessment of Planetary Protection Requirements for Venus Missions: Letter Report (2006)
Distributed Arrays of Small Instruments for Solar-Terrestrial Research: Report of a Workshop (2006)
Issues Affecting the Future of the U.S. Space Science and Engineering Workforce: Interim Report (SSB with the Aeronautics and Space Engineering Board [ASEB], 2006)
Review of NASA's 2006 Draft Science Plan: Letter Report (2006)
The Scientific Context for Exploration of the Moon—Interim Report (2006)
Space Radiation Hazards and the Vision for Space Exploration (2006)

The Astrophysical Context of Life (SSB with the Board on Life Sciences, 2005)
Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation (2005)
Extending the Effective Lifetimes of Earth Observing Research Missions (2005)
Preventing the Forward Contamination of Mars (2005)
Principal-Investigator-Led Missions in the Space Sciences (2005)
Priorities in Space Science Enabled by Nuclear Power and Propulsion (SSB with ASEB, 2005)
Review of Goals and Plans for NASA's Space and Earth Sciences (2005)
Review of NASA Plans for the International Space Station (2005)
Science in NASA's Vision for Space Exploration (2005)

Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report (SSB with ASEB, 2004)
Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report (2004)
Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy (SSB with ASEB, 2004)
Plasma Physics of the Local Cosmos (2004)
Review of Science Requirements for the Terrestrial Planet Finder: Letter Report (2004)
Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics (2004)
Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond (SSB with ASEB and the Board on Atmospheric Sciences and Climate, 2004)

Limited copies of these reports are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W., Washington, DC 20001
(202) 334-3477/ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release, which in some cases precedes the year of publication.

**COMMITTEE ON NASA'S BEYOND EINSTEIN PROGRAM:
AN ARCHITECTURE FOR IMPLEMENTATION**

CHARLES F. KENNEL, University of California, San Diego, *Co-Chair*
JOSEPH H. ROTHENBERG, Universal Space Network, *Co-Chair*
ERIC G. ADELBERGER, University of Washington
WILLIAM B. ADKINS, Adkins Strategies, LLC
THOMAS APPELQUIST, Yale University
JAMES S. BARROWMAN, Independent Consultant
DAVID A. BEARDEN, The Aerospace Corporation
MARK DEVLIN, University of Pennsylvania
JOSEPH FULLER, Jr., Futron Corporation
KARL GEBHARDT, The University of Texas at Austin
WILLIAM C. GIBSON, Southwest Research Institute
FIONA A. HARRISON, California Institute of Technology
ANDREW J. LANKFORD, University of California, Irvine
DENNIS McCARTHY, Independent Consultant
STEPHAN S. MEYER, The University of Chicago
JOEL R. PRIMACK, University of California, Santa Cruz
LISA J. RANDALL, Harvard University
CRAIG L. SARAZIN, University of Virginia
JAMES S. ULVESTAD, National Radio Astronomy Observatory
CLIFFORD M. WILL, Washington University
MICHAEL S. WITHERELL, University of California, Santa Barbara
EDWARD L. WRIGHT, University of California, Los Angeles

Staff

BRIAN D. DEWHURST, Study Director
SANDRA J. GRAHAM, Study Director (from January 29, 2007)
PAMELA L. WHITNEY, Study Director (until January 28, 2007)
VICTORIA SWISHER, Research Associate
CARMELA CHAMBERLAIN, Program Associate
CELESTE A. NAYLOR, Senior Program Assistant
CATHERINE A. GRUBER, Assistant Editor

SPACE STUDIES BOARD

LENNARD A. FISK, University of Michigan, *Chair*
A. THOMAS YOUNG, Lockheed Martin Corporation (retired), *Vice Chair*
SPIRO K. ANTIOCHOS, Naval Research Laboratory
DANIEL N. BAKER, University of Colorado
STEVEN J. BATTEL, Battel Engineering
CHARLES L. BENNETT, Johns Hopkins University
ELIZABETH R. CANTWELL, Los Alamos National Laboratory
ALAN DRESSLER, The Observatories of the Carnegie Institution
JACK D. FELLOWS, University Corporation for Atmospheric Research
FIONA A. HARRISON, California Institute of Technology
TAMARA E. JERNIGAN, Lawrence Livermore National Laboratory
KLAUS KEIL, University of Hawaii
MOLLY MACAULEY, Resources for the Future
BERRIEN MOORE III, University of New Hampshire
KENNETH H. NEALSON, University of Southern California
JAMES PAWELCZYK, Pennsylvania State University
SOROOSH SOROOSHIAN, University of California, Irvine
RICHARD H. TRULY, National Renewable Energy Laboratory (retired)
JOAN VERNIKOS, Thirdage LLC
JOSEPH F. VEVERKA, Cornell University
WARREN M. WASHINGTON, National Center for Atmospheric Research
CHARLES E. WOODWARD, University of Minnesota
GARY P. ZANK, University of California, Riverside

MARCIA S. SMITH, Director

BOARD ON PHYSICS AND ASTRONOMY

ANNEILA L. SARGENT, California Institute of Technology, *Chair*
MARC A. KASTNER, Massachusetts Institute of Technology, *Vice Chair*
JOANNA AIZENBERG, Lucent Technologies
JONATHAN BAGGER, Johns Hopkins University
JAMES E. BRAU, University of Oregon
PHILIP H. BUCKSBAUM, Stanford University
ADAM S. BURROWS, Steward Observatory
PATRICK L. COLESTOCK, Los Alamos National Laboratory
RONALD C. DAVIDSON, Princeton University
ANDREA M. GHEZ, University of California at Los Angeles
PETER F. GREEN, University of Michigan
LAURA H. GREENE, University of Illinois Urbana-Champaign
WICK HAXTON, University of Washington
JOSEPH HEZIR, EOP Group
ALLAN H. MACDONALD, University of Texas
HOMER A. NEAL, University of Michigan
JOSE N. ONUCHIC, University of California at San Diego
WILLIAM D. PHILLIPS, National Institute of Standards and Technology
CHARLES E. SHANK, E. O. Lawrence Berkeley National Laboratory
THOMAS N. THEIS, IBM T.J. Watson Research Center
MICHAEL S. TURNER, University of Chicago
C. MEGAN URRY, Yale University

DONALD C. SHAPERO, Director

Acknowledgments

This report is the product of a large amount of work carried out by many people. The committee extends its thanks and appreciation to all who participated in this endeavor; it would be impossible to name them all individually. The committee thanks the speakers who made formal presentations at each of their meetings; their presentations and the ensuing discussions were extremely informative and had a significant impact on the committee's deliberation. The committee is especially appreciative of the efforts of the time and efforts invested by the missions teams in answering the Request for Information (RFI) and further questions from the committee: ADEPT (Chuck Bennett), CASTER (Mark McConnell), CIP (Gary Melnick), CMBPol (Gary Hinshaw), Con-X (Harvey Tananbaum), DESTINY (Tod Lauer), EPIC-F (James Bock), EPIC-I (Peter Timbie), EXIST (Josh Grindlay), LISA (Tom Prince), and SNAP (Saul Perlmutter and Michael Levi).

The committee is also appreciative of the hard work that SAIC, the independent contractor to the committee, dedicated to assisting the committee in the cost estimation process. SAIC provided the committee with cost estimating expertise and tools for the assessment of probable cost ranges for the candidate BE missions. SAIC dedicated tremendous efforts to completing the cost estimates for the report, and the committee particularly thanks the hard work of Joseph Hamaker and Frank Curran in leading the SAIC team throughout this process.

Finally the committee expresses thanks to ESA and David Southwood, The European Space Agency's Director of Science, who at the invitation of the committee to took the time to come to U.S. and provide important insight into ESA's support of LISA.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Barry C. Barish, California Institute of Technology,
Steven J. Battel, Battel Engineering,
Mitchell C. Begelman, University of Colorado,
Neil Brandt, Penn State University,
John E. Carlstrom, University of Chicago,
Marc Davis, University of California, Berkeley,
Lennard A. Fisk, University of Michigan,
Riccardo Giacconi, Johns Hopkins University,
David J.Gross, University of California, Santa Barbara,
Jeremy N. Kasdin, Princeton University,
J. Patrick Looney, Brookhaven National Laboratory,
Anneila L. Sargent, California Institute of Technology, and
A. Thomas Young, Lockheed Martin Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Martha P. Haynes (NAS), Cornell University, and Dr. Kenneth H. Keller (NAE), Johns Hopkins University School of Advanced International Studies. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents