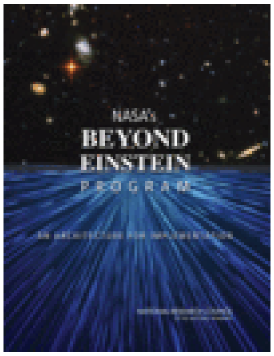

NASA's Beyond Einstein Program: An Architecture for Implementation

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

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NASA's
BEYOND
EINSTEIN
PROGRAM

AN ARCHITECTURE FOR IMPLEMENTATION

Committee on NASA's Beyond Einstein Program: An Architecture for Implementation

Space Studies Board

and

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Division on Engineering and Physical Sciences

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The committee thanks the speakers who made formal presentations at each of its meetings; their presentations and the ensuing discussions were extremely informative and had a significant impact on the committee's deliberations. The committee is especially appreciative of the time and efforts invested by the mission teams in responding to its Request for Information and answering further questions from the committee: ADEPT (Charles 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 (Thomas Prince), and SNAP (Saul Perlmutter and Michael Levi).

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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,
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Anneila I. 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 Martha P. Haynes, Cornell University, and Kenneth H. Keller, 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.

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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 to be 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 planned 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: the Black Hole Finder Probe (BHFP), the Inflation Probe (IP), and the Joint Dark Energy Mission (JDEM). Candidate missions for all of these mission areas are currently in various stages of definition and development.

Prompted by congressional language inserted in the formulation of the fiscal year (FY) 2007 budget, NASA and the Department of Energy (DOE) asked the National Research Council (NRC) to prepare a report reviewing NASA's Beyond Einstein Program. The NRC appointed the Committee on NASA's Beyond Einstein Program to carry out this study. The report was to assess the five proposed Beyond Einstein mission areas and recommend one mission area for first development and launch utilizing a Beyond Einstein Program funding wedge[2] that will start in FY 2009. To accomplish this task, 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 NRC's 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.

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[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 roadmapping effort required under the Government Performance Results Act of 1993 (Public Law No. 103-62).

[2] NASA's FY 2007 budget request projected NASA's level of support for Beyond Einstein missions covering the years FY 2007 through FY 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 funding wedge."

MISSION ASSESSMENTS

The criteria adopted 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 each assessed 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 the proposal's estimated costs versus independent probable cost estimates prepared by the committee.

The committee made its recommendations on the basis of the above criteria, but during its deliberations it 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, relationships in interagency and international partnerships, investments in underlying research and technology and supporting infrastructure, and the impact of International Traffic in Arms Regulations. The committee reviewed these issues in order to understand the broader context of the study.

Using the criteria described above, the committee performed extensive assessments for each mission. 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 (BHFP)

The two Black Hole Finder Probe mission concepts presented to the committee are called EXIST (Energetic X-ray Imaging Survey Telescope) and CASTER (Coded Aperture Survey Telescope for Energetic Radiation). Both of these concepts use wide-field coded-aperture hard x-ray telescopes, divided into arrays of subtelescopes at two different energy bands. With their arrays of subtelescopes, either would survey the entire sky between a few kiloelectronvolts 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.

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 will address the question of how black holes form and grow.

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 a direct impact on a number of important astrophysical questions. BHFP will provide 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 very-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 multiwavelength observational data and theoretical advances (e.g., in black hole accretion modeling) will be necessary in order 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 (TRLs) than that of EXIST, as discussed in Chapter 3 of this report. The estimated costs for both mission concepts are higher than projected in the original Beyond Einstein roadmap: there the Einstein Probes had been envisioned as medium-scale missions that could be executed much more rapidly and cheaply than the flagship LISA and Con-X missions. However, the BHFP probe concepts now have costs that the mission teams estimate are 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 trade-offs 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 (Con-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 Con-X has the potential to make strong contributions to Beyond Einstein science through the study of the evolution of supermassive black holes and the mapping of the dynamics of clusters of galaxies. However, other Beyond Einstein 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 Beyond Einstein funding. The committee concluded that the merits of Con-X can be fully assessed only 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 NRC's 2001 astronomy and astrophysics decadal survey, *Astronomy and Astrophysics in the New Millennium*,[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 committee. Aside from the well-known risks of satellite implementation, a number of technical risks have been called out by the Con-X mission team and are discussed in Chapter 3. Chief among these is the achievement of the needed mirror angular resolution and the development of the position-sensitive microcalorimeters. The Con-X team has reasonable plans to mature both of these technologies, and, given adequate resources and time, there is little reason to expect that these technologies 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 microcalorimeter arrays to improve the Con-X mission's readiness for consideration in the next astronomy and astrophysics decadal survey. The committee, however, does not believe that the current Beyond Einstein funding 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.

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

Inflation Probe (IP)

The Inflation Probe mission effort 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 goal of the Beyond Einstein Program. 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 in order 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 that of 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 a stage of development earlier than that of the CIP. The three CMB proposals outline detector and instrument concepts that are extrapolations from existing experiments. The CMB polarization experiments—Experimental Probe of Inflationary Cosmology (EPIC-F), Einstein Polarization Interferometer for Cosmology (EPIC-I), and CMB Polarimeter (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 Space Agency's (ESA's) Planck mission is successful, it will go a long way but not all the way toward proving the readiness of the detector technology. Along with the continued investment in grating technology required to continue to mature CIP, significant continued support of detector and ultracool cryocoolers (sub-100 mK) is needed to push the three polarization missions along. Given the missions' 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 technology of the polarization missions, CIP would benefit from intensive theoretical investigations as well as further refinement of grating technologies.

Joint Dark Energy Mission (JDEM)

The Joint Dark Energy Mission is a partner mission between NASA and DOE that would use an optical-to-near-infrared wide-field survey telescope to investigate the distribution of dark energy. Three concepts for a JDEM 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 this 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 proposed by ADEPT, 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 grew, along with data for many other astrophysics studies. A low-background, wide-field imaging survey, such as proposed by DESTINY and SNAP, would provide a much larger diffraction-limited near-infrared survey than would be available otherwise. Such a survey would revolutionize the understanding of how and when galaxies acquire their mass, as well as providing 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 do, 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 data sets. Cross-checking with large, statistically significant data sets should help to 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 TRLs of 5-6 or higher. (The SNAP charge-coupled devices are an exception at TRL 4-5, but there is a good plan to bring them to flight readiness.) The ADEPT team did not provide the committee with adequate data to evaluate readiness, but in general the team's critical technology has flight heritage and no major challenges.

Laser Interferometer Space Antenna (LISA)

The proposed Laser Interferometer Space Antenna is a gravitational-wave antenna. At the low frequencies where a rich variety of strong signals are expected to exist, gravity waves can be detected only 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 5-year mission, LISA is expected 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 black holes and the formation of galactic structure, to test general relativity in the strong-field dynamical regime, and to determine if the black holes in 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 faraway 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 the following: micronewton thruster technology development and lifetime tests; the point-ahead actuator; the phase measurement system; and laser frequency noise suppression. As discussed in this report, these were assessed to be at TRLs of 4 or less.

Cost Realism

The committee was 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 with 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 Beyond Einstein 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 funding 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 these data to indicate how the JDEM and LISA development and funding profiles could be adjusted to fit within NASA's funding wedge, given that DOE expects to cofund JDEM up to approximately \$400 million[4] and ESA plans approximately \$500 million for LISA.[5]

MAJOR FINDINGS AND RECOMMENDATIONS

In light of the considerations summarized above and described in considerably more detail in the body of this report, the committee developed 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 Program 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 (BE) missions. While Con-X 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.

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[4] Kathy Turner, Program Manager, Office of High Energy Physics, Department of Energy, "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, ESA Director of Science, in discussions on ESA's Astrophysics and Fundamental Physics Program, April 5, 2007.

Finding 4. LISA is an extraordinarily original and technically bold mission concept that will open up an entirely new way of observing the universe, with immense potential to enlarge the 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 that 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 the 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 candidates identified thus far are based on instrument and spacecraft technologies that either have been flown in space or have been extensively developed in 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 proposals 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 next 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 committee's next-highest priority for funding from the current 2009 Beyond Einstein NASA funding wedge is to accelerate the maturation of those mission-critical LISA technologies that are currently at low TRLs. 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 that all their component missions require additional technology maturity before they can be fully evaluated. Their technology development should continue to be supported in NASA's broader astrophysics program, at least at a level that allows a sound appraisal by the next astronomy and astrophysics decadal survey.

1

Introduction

PHYSICS AND ASTRONOMY IN EINSTEIN'S CENTURY

As the 20th century came to a close, astronomers discovered something that challenged the basic understanding of physics developed over the entire century: dark energy.

The 20th century opened with the development of Albert Einstein's theory of special relativity, published in 1905, which gave science a radically new way of understanding how space and time are related through the propagation of light. Between 1911 and 1916, Einstein generalized his theory to include gravity. This immediately became science's best tool for understanding the large-scale structure of the universe. In 1929, Edwin Hubble found that distant galaxies are all moving away from us. Einstein's theory of general relativity provided a natural framework for astronomers' observations of the completely unexpected recession of galaxies in the distant universe—space itself is expanding.

While those advances were occurring in astronomy, physicists were developing quantum theory, an entirely new way of viewing the world of the extremely small: of atoms, nuclei, and electrons. By 1930, the basic structure of atoms and molecules was understood, and physicists were moving on to probe the even smaller nucleus. Astronomers and physicists were making discoveries at opposite ends of the size and distance scales, and they were not in a position to see the connections between their research at that time.

Just before World War II, physicists developed high-energy accelerators to probe deeper inside atomic nuclei and, later, inside the building blocks of the nucleus—protons and neutrons. A series of successively higher-energy accelerator experiments discovered many new "elementary" particles in the succeeding decades. By the 1970s, a "standard model" of what some people had called a "zoo" of new particles had been formulated. The Standard Model still summarizes nearly everything that has been learned experimentally about elementary particles to date.

In the decades after World War II, astronomers got their first indications of an exotic consequence of Einstein's relativity: collapsed stars and galactic cores called black holes—black because their gravity is so intense that no light can escape from them. Astronomers now know that black holes are found in nearly every galaxy, including our own. They also inferred from observing neutron stars in orbit that the gravitational waves predicted by Einstein must exist, although scientists still have not detected them directly. Astronomers also began to suspect that their telescopes were not seeing all the kinds of matter in the universe. They inferred that there must be unseen "dark" matter that exerts a gravitational pull on the motions of stars in galaxies and on the motion of galaxies in galaxy clusters. Dark matter is now thought to be ubiquitous, comprising over 20 percent of the mass-energy density of the observed universe. If the dark matter is an elementary particle, it cannot be one of those in the Standard Model. The Standard Model is incomplete. Astronomy was beginning to pose challenges to physics.

By the 1980s, the expanding universe had gotten its own theoretical model, which is by now so well verified that it deserves also to be called standard: the so-called Inflationary Big Bang Model. At its earliest moments, our entire universe was unimaginably small and unimaginably hot. It suddenly "inflated" in a "big bang." The Inflationary Big Bang Model naturally explains why the universe appears to us so nearly flat and so nearly uniform in all directions. The universe continued to expand after the brief episode of rapid inflation ended; this evolved into the expansion that Edwin Hubble first observed. As the universe expanded it cooled, and its composition changed from particles only found by accelerators today to the hydrogen and helium atoms currently observed. This process was completed after about 300,000 years, when electrically charged electrons and ions first combined into these atoms.

In the 1990s, astronomers showed with exquisite precision that microwaves almost uniformly filling the universe in all directions today are the light radiation created when atoms first formed. This cosmic background radiation was subsequently shifted to longer wavelengths by the ongoing expansion of the universe. Precision observations of the microwave background not only confirmed many aspects of the Inflationary Big Bang Model but also became an important tool for learning more about both physics and astronomy.

A NEW ERA IN PHYSICS AND ASTRONOMY

By 1995, astronomers and physicists could be reasonably satisfied with their century's work. Einstein's theory of relativity, the Standard Model of particle physics, and the Inflationary Big Bang Model had passed the experimental tests that science had devised in the past two generations. With the exception of the dark matter puzzle, the foundations seemed reasonably solid, as far as they went. However, Einstein's relativity and basic particle physics were now irretrievably entangled with one another, and understanding the relationship between the two had become one of the central unanswered questions of contemporary science.

In 1998, astronomy again shook the foundations of physics. Astronomers, by relating the apparent brightness of Type Ia supernovas in distant galaxies to their speed of recession, found that the expansion of the universe—of space itself—is *speeding up*. The speedup implies the existence of a new kind of energy, "dark energy," that comprises 70 percent of the total mass-energy density in the universe. Einstein's equations for an expanding universe allow a so-called cosmological constant that acts the same everywhere and, within today's observational limits, could account for the speedup. However, basic physics theories have no natural explanation for the size of the observed acceleration rate.

The discovery of dark energy has caused huge excitement. The questions fly thick and heavy. Can an understanding of dark energy (and dark matter) teach us ways in which particle physics models should be extended? Should we not test the degree to which dark energy is exactly constant, as Einstein's cosmological constant predicts? Or, going beyond Einstein, will we find that it varies? Can the distant universe be observed with the exquisite precision needed to detect its variation? If dark energy does vary, what would be learned about the physics of particles? Either answer—constant or varying—has profound implications for both physics and astronomy. There is renewed interest in testing Einstein's theory. Should we not now investigate general relativity experimentally where it has never been tested before—in the so-called strong-field regime? Can we do this by observing the gravitational waves generated when two black holes merge. Will this be how we first detect gravitational waves directly? What will be learned when we do detect them directly? Will it be found that there are deviations from Einstein's general relativity? Can we detect the gravitational waves generated at the moment of inflation? If so, will we learn about particle energy scales vastly higher than those attainable in accelerators? Do atoms behave in unexpected ways when they are at the high temperatures and pressures associated with the strong gravitational field near a black hole? Shouldn't a more complete census of black holes be made?

Amidst all the new questions awaiting answers, two points emerge with clarity. The first is that the 21st century in astronomy and physics will be very different from the 20th. We are going to have to go beyond Einstein. Second, the understanding of the inflationary big bang universe is sufficiently secure that scientists can use the universe itself the way they use accelerators: to explore the most basic laws of physics. Astronomers and physicists will be working together in mutually supportive ways from now on.

EVOLUTION OF THE U.S. STRATEGY FOR MOVING "BEYOND EINSTEIN"

NASA did not wait long to explore the implications of the new discoveries. In 1999 NASA asked the National Research Council's (NRC's) Board on Physics and Astronomy to identify the most exciting science at the interface of physics and astronomy. The resulting report, *Connecting Quarks with the Cosmos*,[1] was developed by physicists and astronomers working together. *Connecting Quarks with the Cosmos* became one of two foundational NRC documents for NASA's Beyond Einstein Program, the other being the NRC decadal survey of astronomy and astrophysics, *Astronomy and Astrophysics in the New Millennium*.[2]

The 2001 decadal survey began by laying out the fundamental goal of the field: "to understand how the universe and its constituent galaxies, stars, and planets formed, how they evolved, and what their destiny will be." To achieve this goal, the report said, astronomers must pursue a balanced strategy with several elements:[3]

> - Survey the universe and its constituents, including galaxies as they evolve through cosmic time, stars and planets as they form out of collapsing interstellar clouds in our galaxy, interstellar and intergalactic gas as it accumulates the elements created in stars and supernovae, and the mysterious dark matter and perhaps dark energy that so strongly influence the large-scale structure and dynamics of the universe.
> - Use the universe as a unique laboratory for probing the laws of physics in regimes not accessible on Earth, such as the very early universe or near the event horizon of a black hole.
> - Search for life beyond Earth, and if it is found, determine its nature and its distribution.
> - Develop a conceptual framework that accounts for all that astronomers have observed.

The first and second elements above relate to the issues taken up in this report.

Connecting Quarks with the Cosmos contrasted the approaches of physicists and astronomers to science:

> Elementary particle physicists and astronomers work at different extremes, the very small and the very large. They approach the physical world differently. Particle physicists seek simplicity at the microscopic level, looking for mathematically elegant and precise rules that govern the fundamental particles. Astronomers seek to understand the great diversity of macroscopic objects present in the universe—from individual stars and black holes to the great walls of galaxies. There, far removed from the microscopic world, the inherent simplicity of the fundamental laws is rarely manifest.[4]

Blending these two ways of looking at nature has already put us on the verge of very important new insights, and we are only at the beginning. After discussing the scientific opportunities immediately ahead and taking into account the decadal survey, *Connecting Quarks with the Cosmos* recommended a suite of space missions with the following goals, among others:

> - Measure the polarization of the cosmic microwave background with the goal of detecting the signature of inflation. The committee recommends that NASA, NSF, and DOE undertake research and development to bring the needed experiments to fruition. . . .
> - Determine the properties of dark energy. The committee supports the Large Synoptic Survey Telescope project, which has significant promise for shedding light on the dark energy. The committee further recommends that NASA and DOE work together to construct a wide-field telescope in space to determine the expansion history of the universe and fully probe the nature of dark energy. . . .

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[1] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003.

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

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

[4] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003, p. 9.

- Use space to probe the basic laws of physics. The committee supports the Constellation-X and Laser Interferometer Space Antenna missions, which hold great promise for studying black holes and for testing Einstein's theory in new regimes. The committee further recommends that the agencies proceed with an advanced technology program to develop instruments capable of detecting gravitational waves from the early universe.[5]

NASA then asked its Space Science Advisory Committee (SSAC) to formulate a program plan in light of the decadal survey and *Connecting Quarks with the Cosmos*. SSAC turned to its Structure and Evolution of the Universe Subcommittee (SEUS) and asked it to develop an implementation roadmap as part of the 2003 strategic plan of NASA required under the Government Performance Results Act of 1993 (Public Law No. 103-62). SEUS coined the term "Beyond Einstein"; its report, *Beyond Einstein: From the Big Bang to Black Holes*,[6] proposed the following program architecture:

> The Beyond Einstein program has three linked elements. . . . The central element is a pair of Einstein Great Observatories, Constellation-X and LISA. . . . The second element is a series of competitively selected Einstein Probes, each focused on one of the science questions, (a joint dark energy mission (JDEM), an inflation probe, and a black hole finder). The third element is a program of technology development, theoretical studies, and education, to support the Probes and the vision missions. . . .

In 2004, the White House Office of Science and Technology Policy (OSTP) released *Physics of the Universe*, an interagency study that illustrates and defines the mutual interest in Beyond Einstein science shared by the Department of Energy (DOE), the nation's principal sponsor of elementary-particle physics; NASA, the nation's principal sponsor of space astronomy; and the National Science Foundation (NSF), the nation's principal sponsor of general science. As one consequence, NASA and DOE agreed to develop a Joint Dark Energy Mission (JDEM), one of the five mission areas included in NASA's Beyond Einstein roadmap.

THE CHARGE TO THE COMMITTEE

The present assessment was prompted by congressional language inserted in the formulation of the fiscal year (FY) 2007 budget. According to Senate Report 109-274 accompanying the Energy and Water Appropriations Bill of 2007:

> The Committee is concerned that the joint mission between the Department of Energy and NASA is untenable because of NASA's reorganization and change in focus toward manned space flight. The Committee directs the Department (of Energy) to immediately begin planning for a single-agency space-based dark energy mission.

Similar language was inserted in House Report 109-474 accompanying the Energy and Water Development Appropriations Bill of 2007:

> NASA has failed to budget and program for launch services for JDEM. Unfortunately, in spite of best intentions, the multi-agency aspect of this initiative poses insurmountable problems that imperil its future. Therefore, the Committee directs the Department [of Energy] to begin planning for a single-agency dark energy mission with a launch in fiscal year 2013.

The administration responded with the approach described here: In August 2006, OSTP Director John H. Marburger convened a meeting of the NASA administrator, the DOE science undersecretary, and the respective chairs of the NRC Space Studies Board, the NRC Board on Physics and Astronomy, and the joint DOE/NASA/NSF Astronomy and Astrophysics Advisory Committee. The purpose of this meeting was to encourage a fair, joint-agency process for going forward on a Beyond Einstein mission.

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[5] National Research Council, 2003, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., pp. 6-7.

[6] National Aeronautics and Space Administration, 2003, *Beyond Einstein: From the Big Bang to Black Holes*, Washington, D.C., January.

NASA and DOE then requested that the NRC assess NASA's Beyond Einstein Program plan according to the following charge,[7] and the NRC established the Committee on NASA's Beyond Einstein Program: An Architecture for Implementation[8] to carry out the charge:

> 1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder Probe) and ***recommend which of these five should be developed and launched first*** [emphasis added], using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:
>
>   - Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
>   - Realism of preliminary technology and management plans, and cost estimates.
>
> 2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

This report adopts terminology that is slightly different from that employed in the charge. Constellation-X (Con-X) and the Laser Interferometer Space Antenna (LISA) are specific single-mission candidates, whereas three candidates for the Joint Dark Energy Mission, four for the Inflation Probe (IP), and two for the Black Hole Finder Probe (BHFP) were submitted to this committee for assessment. The committee distinguishes between the five *mission areas* listed in the charge above and the 11 individual *mission candidates*. The committee also notes that both the LISA and the JDEM mission areas are proposed as NASA collaborations (with the European Space Agency and the DOE's Office of Science, respectively) and that there is the possibility that the other mission areas may also involve partner organizations in the future. The committee assumes that organizations interested in partnering with NASA on such missions would be motivated by similar scientific and technical goals.

THE COMMITTEE'S APPROACH TO ITS CHARGE

The committee started with a systematic consideration of each of the 11 mission candidates identified thus far in the five mission areas in the Beyond Einstein Program plan. The committee invited presentations from agency leaders in NASA, DOE, and the European Space Agency, and at least two presentations from each team proposing a mission candidate. Additionally, the committee heard presentations from individual scientific leaders and listened to the broader scientific community in town hall meetings across the United States (see Appendixes C and D). Subsequently, the committee asked clarifying questions of each team and included their written responses in the committee's assessment process (see Appendixes E and F).

Using these inputs, the committee then assessed each mission candidate for its scientific excellence, its response to Beyond Einstein goals, its broad contributions to science, its competition from other space- and ground-based projects in the United States and abroad, and its scientific readiness. On the implementation side, the committee assessed each mission candidate for its cost, complexity, schedule, and related programmatic implications and for its stage of development and overall technical readiness, and identified pertinent individual factors. The committee carried out these steps before any formal discussion of Task 1 of its charge, and only then did it begin a comparative discussion to identify the main competitors for the Task 1 recommendation.

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[7] See Appendix A for the letter of request and Appendix B for the full statement of task.

[8] See Appendix I for committee member biographies.

OUTLINE OF THE REPORT

Chapter 2 assesses the contribution that each mission candidate would make to three central Beyond Einstein science questions: What powered the big bang? How do black holes manipulate space, time, and matter? and What is the mysterious dark energy pulling the universe apart? Chapter 2 summarizes the strengths, scientific uncertainties, readiness, and uniqueness of the mission candidates and associated scientific programs. It should be noted that since the mission candidates vary greatly in their stage of development, the mission assessments necessarily differ in their level of detail in both Chapters 2 and 3.

Chapter 3 examines the technical and programmatic challenges presented by each of the 11 Beyond Einstein mission candidates. The committee assessed team organization, project management, technology readiness and difficulty, cost and schedule risks, and technical and cost margins; it also identified special challenges particular to each mission candidate. Chapter 3 can be used as a summary reference for Beyond Einstein mission readiness as of FY 2007. The committee's intent has been to provide a basis for judging the readiness of each mission to proceed to a Formulation Phase A (conceptual design phase) in FY 2009, and to support its advice on how best to prepare each mission area for consideration by the NRC's forthcoming decadal survey.

Chapter 4 discusses policy and overarching programmatic issues associated with the Beyond Einstein Program, including implications for U.S. science and technology leadership, program funding constraints, the role of interagency and international partnerships, the broader uses of investments in research and technology infrastructure, and the implications of International Traffic in Arms Regulations. Such issues are representative of those faced by most cutting-edge space science programs.

Chapter 5 contains the committee's eight major findings and three principal recommendations. The findings are not listed in priority order; their order expresses the progression of reasoning that led to the three principal conclusions. The chapter also summarizes the committee's overall assessments of each of the Beyond Einstein mission candidates and provides advice on how to move each mission area forward until it can be considered by the decadal survey.

2

Science Impact

ASSESSMENT CRITERIA AND CONSIDERATIONS

What powered the big bang? What happens to spacetime near a black hole? What is the mysterious dark energy pulling the universe apart? These fundamental questions lie at the heart of NASA's Beyond Einstein Program.[1] Einstein's theory of general relativity predicted the expansion of the universe from a big bang and the phenomenon of black holes. Einstein's general relativity equation contains a term associated with a "cosmological constant" that may describe dark energy. Investigating the nature of these phenomena—going beyond Einstein—will take space missions that harness the ingenuity, creativity, and technical sophistication of current and future generations.

The Beyond Einstein roadmap[2] lays out specific research goals related to each of the three fundamental questions above. Investigating what powered the big bang requires probing the period of inflation, an early era when the universe expanded by some 30 orders of magnitude in linear scale. According to theory, inflation produced gravitational radiation, and a specific goal is to detect the level of this radiation, either directly or through its residual imprint on matter. Progress on this question will also be made by determining the size, shape, age, and energy content of the universe, which will better constrain conditions during the big bang.

To understand how black holes affect space, time, and matter in the universe, one must first determine how frequently they occur, what their properties are, and how they interact with matter in galaxies and other structures. Thus, two of the research goals associated with black holes are to perform a census of black holes and to determine how they are formed and evolve. A third objective is to probe what happens in the very strong gravitational field very near a black hole by observing distortions of spacetime near its event horizon. A final objective is to observe what happens to gas and stars as they are swallowed by black holes.

Understanding the nature of dark energy is the most pressing question in cosmology today. The research goal that has greatest promise of elucidating the nature of dark energy is the determination of its cosmic evolution. Determining the size, shape, age, and energy content of the universe is also necessary in order to constrain the properties of dark energy.

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[1] National Aeronautics and Space Administration, *Beyond Einstein: From the Big Bang to Black Holes*, Washington, D.C., January 2003, p. 5.

[2] 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 roadmapping effort required under the Government Performance Results Act of 1993 (Public Law No. 103-62).

The mission suite designed in the Beyond Einstein roadmap to carry out the program's research goals consists of two flagship missions, the Laser Interferometer Space Antenna (LISA) and Constellation-X (Con-X), as well as three smaller missions known as the Einstein Probes. The flagship missions are well defined and mature in their scientific formulation. The Einstein Probes—the Cosmic Inflation Probe (CIP), the Black Hole Finder Probe (BHFP), and the Joint Dark Energy Mission (JDEM)—are typically smaller in scale, and multiple technical or observational approaches are being considered for their implementation. A competitive review will determine which of the implementation approaches of a given probe concept will be selected. The committee considered the scientific questions for each class of probe, as well as all proposed observational approaches, in reaching its conclusions about each mission area.

As one of its overall criteria for evaluating the Beyond Einstein missions, the committee formulated a set of five criteria for use in assessing the scientific content and quality of the mission candidates. These criteria characterize the scientific readiness, risk, and progress that each mission promises relative to the Beyond Einstein science goals. These science goals are well conceived and are traceable through numerous strategy and planning documents, and the committee has therefore chosen to adopt them as well.

- *Advancement of Beyond Einstein research goals.* The primary assessment criterion is how directly and unambiguously a mission candidate addresses the Beyond Einstein research goals.
- *Broader science contributions.* Many of the mission candidates in the Beyond Einstein portfolio can provide data that are central to other astrophysical investigations not identified as part of the Beyond Einstein research goals.
- *Potential for revolutionary discovery.* Will the mission candidate's measurements truly alter current paradigms, or discover new and unexpected phenomena?
- *Science risk and readiness.*[3] Considering the mission candidate as designed, how much risk is there that the measurements will not answer the questions posed? This risk could be due either to systematic effects associated with astronomical phenomena not easily addressed with theory, or to uncertainties in the levels of the signal to be measured or the number of accessible astronomical sources. Are the theoretical frameworks for understanding the measurements in place? Are there foundational measurements that need to be made first (e.g., characterization of astronomical backgrounds, wide-field surveys to find targets, and so on)?
- *Uniqueness of the mission candidate for addressing the scientific questions.* Are there other projects, either space- or ground-based, that are likely to compete in addressing Beyond Einstein questions before the completion of the mission in question? How essential is the vantage point of space for the proposed science?

This chapter describes the science goals, potential impact, and scientific readiness of each of the five mission candidates. Note that because the current state of development varies greatly among missions, the level of detail in the following mission discussions varies as well. The chapter concludes with a comparative assessment of progress to be made against each of the three Beyond Einstein questions.

BLACK HOLE FINDER PROBE

Introduction

The Black Hole Finder Probe is one of the three Einstein Probes discussed in the Beyond Einstein roadmap. BHFP is designed to find black holes on all scales, from one to billions of solar masses. BHFP will address the question "How did black holes form and grow?" by observing high-energy x-ray emissions from accreting black holes and explosive transients. With a very wide field of view, BHFP can detect variable sources and bursts of x-rays that herald the birth of new black holes and map high-energy x-ray sources over the entire sky. By operating in the hard x-ray band (a few to 600 keV), BHFP can detect accreting black holes that are surrounded by obscuring

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[3] This criterion is focused on scientific challenges inherent in the investigation, assuming that the technology challenges are or can be met. The technology challenges for each mission are addressed in Chapter 3.

TABLE 2.1 Black Hole Finder Probe: Mission Description

Parameter	Value
Primary measurement	Hard x-ray all-sky survey
Observatory type	Coded-aperture telescope, 10-600 keV or 3-600 keV
Projected years in orbit	5-yr primary mission, 10-yr goal
Type of orbit	500 km altitude, circular orbit
Mission phases	One-phase, full-time scanning survey
Science operations	Continuous survey, with gamma-ray burst/variable alerts
Other mission characteristics	Covers entire sky at sub-day intervals

material and are therefore not visible in the traditional x-ray bands below 10 keV (if they lie at low redshift). With sensitivity that is 10 to 100 times that of previous hard x-ray wide-field telescopes, BHFP can make a census of the accreting black hole population in local galactic nuclei over a wide range in luminosity, as well as detect the brightest sources out to redshifts of approximately 2.

The BHFP instrument would consist of multiple coded-aperture “subtelescopes,” each covering fully coded fields of view (FOVs) roughly 20 degrees on a side; the combined FOV of these subtelescopes is a fan beam covering nearly 180 degrees in its long dimension. The spacecraft would fly in a circular low Earth orbit with an altitude of approximately 500 km and would cover the entire sky by zenith-pointing and undergoing a nodding motion so that the fan beams would cover a full 180 degrees during each orbit. Because of the multiple detector units, the BHFP has a rather high mass, in the vicinity of 10,000 kg. Table 2.1 lists the primary mission parameters for BHFP.

Two concepts for a BHFP mission were presented to the committee: EXIST (Energetic X-ray Imaging Survey Telescope) and CASTER (Coded Aperture Survey Telescope for Energetic Radiation). Both concepts employ a wide-field coded-aperture hard x-ray survey telescope, differing primarily in their detector implementation. Each would divide its total energy coverage into a high-energy and low-energy band. EXIST would extend to a somewhat lower energy, down to 3 keV, to provide more detailed spectral energy distributions and reach the iron-line complex near 6.4 keV. Both EXIST and CASTER cover the energy range up to 600 keV, primarily to ensure access to the 511 keV electron-positron annihilation line. The accuracy of source positions is determined by the properties of the coded apertures and the strengths of the individual sources; for EXIST, the best position accuracy cited is 11 arcseconds (arcsec) (for 5σ sources) for the Low Energy Telescope (LET) and 56 arcsec for the High Energy Telescope (HET), while CASTER predicts position accuracies (for 10σ sources) of 42 arcsec for the Low Energy Imager (LEI) and 70 arcsec for the High Energy Imager (HEI). Table 2.2 summarizes the observational parameters of the scientific instruments, with separate entries for EXIST and CASTER. Note that the BHFP, as embodied in EXIST, is the only Einstein Probe that was specifically recommended in the National Research Council’s (NRC’s) decadal survey report *Astronomy and Astrophysics in the New Millennium*, published in 2001.[4]

Mission Science Goals

Contribution to Beyond Einstein Science Goals

Three specific Research Focus Areas of the Beyond Einstein roadmap may be addressed by the BHFP and are discussed briefly in this section. Table 2.3 summarizes some of the key science questions that will be investigated by BHFP as part of these Research Focus Areas.

Perform a Census of Black Holes Throughout the Universe. For Beyond Einstein, the most directly relevant science goal of the BHFP is to perform a census of black holes throughout the universe. The proposed realizations

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

TABLE 2.2 Black Hole Finder Probe: Mission Instrument Properties

Instrument	Spectral Range (keV)	Angular Resolution (arcmin)	Spectral Resolution[a] (ΔE/E)	Collecting Area[b] (m^2)	Field of View (degrees)
EXIST-HET	10-600	6.9	2% at 100 keV 1% at 511 keV	2.7 at 10 keV 2.7 at 100 keV 0.7 at 511 keV	65 × 154
EXIST-LET	3-30	1.4	5% at 10 keV	0.6 at 10 keV	64 × 160
CASTER-HEI	200-600	12	~5% at 511 keV	1.4 at 511 keV	40 × 160
CASTER-LEI	10-200	7	~35% at 10 keV ~10% at 100 keV	3.1 at 10 keV 3.1 at 100 keV	40 × 160

NOTE: See Appendix G in this report for definitions of acronyms.

[a] The spectral resolution for CASTER has not yet been optimized; values cited are intermediate between those for the current prototype and the best published results.

[b] Only a few of the detectors see a given point on the sky at one time. The areas given are the total detection areas that are exposed to any part of the sky at a given time. Effective areas exposed to a particular point on the sky at a given time are between 10 percent and 20 percent of the values tabulated here.

of the BHFP would carry out this census from low Earth orbit, using coded-aperture telescopes to survey x-ray emission at energies ranging from a few kiloelectronvolts to 600 keV. Previous x-ray surveys at energies below 10 keV are not sensitive to low-redshift active galactic nuclei (AGNs) with highly obscured nuclei (at high redshift, the absorption cutoff shifts into the traditional 1-10 keV x-ray band). This sensitivity is important, as evidence suggests that a substantial fraction of the nearby accretion energy from massive black holes has been obscured from the view of lower-energy x-ray missions.[5] At the higher energies, the sensitivities of the BHFP would be up to 100 times better than the present INTEGRAL and Swift missions, leading to the expected detection of as many as 30,000 to 100,000 extragalactic hard x-ray sources. The proposed missions will localize 10-100 keV sources with an angular location accuracy of tens of arcseconds, with the sensitivity to detect objects having x-ray luminosities (L_x) ~10^{44} ergs s^{-1} out to redshifts (z) of 0.25 and (L_x) ~10^{46} ergs s^{-1} out to z ~2. Previous studies indicate that AGNs with x-ray luminosities ~10^{46} ergs s^{-1} are fairly rare, so the sample detected at high redshift may be fairly small. Thus, a wide range of black holes with masses of a million to a billion solar masses will be detected at low redshift, but only the most luminous AGNs (and most massive black holes) will be seen from the first few billion years of the universe. Within our own Galaxy and its nearest neighbors, several thousand stellar-mass black holes, both isolated and in binary systems, will be detected as they accrete matter from their surroundings or their companions.

Determine How Black Holes Are Formed and How They Evolve. The formation and evolution of black holes can be studied by two means. The census of x-ray sources described in the preceding subsection will provide x-ray luminosities for massive black holes, which are related to the accretion rates and hence to the black hole growth rates. Thus, by a somewhat indirect chain of reasoning, the x-ray luminosity studies can tell us how massive black holes grow in mass as the universe evolves.

The other primary means of studying black hole formation and evolution is by monitoring high-energy x-ray variability. A very extreme form of x-ray variability is displayed by gamma-ray bursts (GRBs), and the BHFP will be a GRB detector of unprecedented sensitivity—perhaps 10 times more sensitive than Swift. Thus, it will detect the formation of stellar-mass black holes throughout the universe by both core-collapse ("long" GRBs) and merging compact objects (likely associated with "short" GRBs). The BHFP will re-image large portions of the

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[5] C.B. Markwardt, J. Tueller, G.K. Skinner, N. Gehrels, S.D. Barthelmy, and R.F. Mushotzky, 2005, The Swift/BAT High-Latitude Survey: First results, *Astrophys. J.* 633:L77-L80.

TABLE 2.3 Black Hole Finder Probe (BHFP): Beyond Einstein Science Programs

Science	Program	Program Characteristics		Program Significance
Science definition programs	All-sky hard x-ray survey	Science question	Perform a census of black holes throughout the universe	The BHFP all-sky survey will detect tens of thousands of hard x-ray sources, determining the population distribution of massive black holes in external galaxies and their contribution to the x-ray background. The x-ray luminosities also will help determine how black holes evolve (see science question below) by providing a characterization of the accretion rates of massive black holes. In addition, the all-sky survey will detect and characterize the emission from several thousand stellar-mass black holes in our Galaxy, undoubtedly finding new rare objects.
		Measurements	All-sky survey in a 10-600 keV (CASTER) or a 3-600 keV (EXIST) range	
		Quantities determined	X-ray flux at low and high energies; source localization of tens of arcsec; location and widths of strong x-ray lines	
	Hard x-ray variability study	Science question	Determine how black holes evolve; observe stars and gas plunging into black holes	The study of variability of extragalactic hard x-ray sources will be used to assess the accretion rates, and hence the rate of growth, of massive black holes. In addition, BHFP will detect rare events in which massive black holes shred and capture the matter from stellar-mass objects that approach too closely.
		Measurements	Variability of hard x-ray sources	
		Quantities determined	Flux vs. energy for hard x-ray sources around the sky, on time scales from milliseconds to days	
	Gamma-ray bursts (GRBs)	Science question	Determine how black holes are formed	The formation rate of stellar-mass black holes over cosmic time, including their possible formation earlier than the first galaxies that scientists have detected to date, can be probed by detecting a significant population of GRBs at high redshift. These distant GRBs may herald the formation of stellar-mass black holes that provide seeds for the eventual evolution to the massive black holes seen at the centers of galaxies.
		Measurements	Detection and characterization of GRBs	
		Quantities determined	Flux vs. time of over a thousand GRBs, with telemetry to ground enabling rapid identification of host galaxies for follow-up	

sky on time scales of hours, thus studying the evolution of the brightest x-ray sources on these short time scales. Ultraluminous x-ray sources, perhaps due to black holes with "intermediate" masses between tens and thousands of solar masses,[6] will be detected in many nearby galaxies. Their total density and duty cycles will allow inferences to be drawn regarding both their overall formation rates and their importance as possible seeds for the growth of more massive black holes.

Observe Stars and Gas Plunging into Black Holes. The unique BHFP capability of studying short time-scale variability of hard x-rays will result in the unprecedented detection of the tidal disruption and "swallowing" of stars by massive black holes; several possible cases have been reported in the literature.[7] Tidal disruptions of stars by massive black holes in relatively nearby galaxies will be detectable in approximately 10 galaxies per year. Such events will provide critical evidence regarding the rates at which massive black holes grow and the conditions most favorable for their growth.

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[6] M.C. Miller and D.P. Hamilton, 2004, Production of intermediate-mass black holes in globular clusters, *Mon. Not. R. Astron. Soc.* 330:232-240.

[7] S. Komossa, J. Halpern, N. Schartel, G. Hasinger, M. Santos-Lleo, and P. Predehl, 2004, A huge drop in the x-ray luminosity of the nonactive galaxy RX J1242.6-1119A, and the first postflare spectrum: Testing the tidal disruption scenario, *Astrophys. J.* 603:L17-L20. S. Komossa, 2002, X-ray evidence for supermassive black holes at the centers of nearby, non-active galaxies, *Rev. Mod. Astron.* 15:27.

Contribution to Other Science

The sources of the x-ray background up to 10 keV have been identified by the Chandra X-ray Observatory.[8] However, the bulk of the energy in the cosmic x-ray background resides in the higher energy regime, and the nature of the objects emitting between 10 and 600 keV still is not determined. By providing a census of extragalactic hard x-ray sources, BHFP can help determine whether the background is due to massive black holes or to some other set of point sources. A key reason for extending the BHFP energy range up to 600 keV is to study the poorly resolved 511 keV electron-positron annihilation line in the Galaxy;[9] BHFP will have the angular resolution to study the spatial distribution of sources in the direction of the Milky Way bulge and will conduct sensitive searches for point components. BHFP's ability to monitor the variability of blazars (black holes with jets oriented along our line of sight) over a wide range of time scales in the crucial hard x-ray band will be, when combined with gamma-ray and radio data, important to understanding how these phenomenal jets are formed and how they accelerate particles to high energy. Finally, BHFP will use its low-resolution spectroscopic capability to measure spectral lines from supernova remnants and neutron stars, thus inferring the local supernova rate. Table 2.4 summarizes some of the supplementary science for BHFP, as well as its capability for making unexpected discoveries (see the following subsection).

Opportunity for Unexpected Discoveries

The primary opportunity for unexpected discoveries will come from the unprecedented measurements of hard x-ray time variability made possible by BHFP. At any given instant, the field of view of BHFP will be more than 10 percent of the entire sky (19 percent of 4π instantaneous FOV for EXIST, full 4π coverage for EXIST or CASTER during a day), with a sensitivity of roughly 1 mCrab over the course of a day. Thus, BHFP will have an unprecedented sensitivity to rare events giving rise to hard x-ray flares. Possible flaring sources might include new types of magnetars and x-ray pulsars, association of gamma-ray bursts with new types of supernovas, ultraluminous x-ray sources in merger galaxies, and x-ray flares associated with black hole mergers detected by LISA. Since the sky at hard x-ray energies has never been surveyed by an instrument with BHFP sensitivity and positional accuracy of tens of arcseconds, entirely new classes of quasi-steady sources of hard x-rays also may be identified.

Assessment of Scientific Impact

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. Some of the most significant are described below. Because of the great advances that BHFP will make in measuring the variable high-energy sky, which to date has only been crudely mapped, some of the impact is certain to come from new phenomena that have not yet been anticipated.

The deepest hard x-ray (above ~20 keV) surveys to date, by the Swift and INTEGRAL spacecraft, have yielded only a few hundred sources,[10] not enough to probe very far into the hard x-ray luminosity function. The increase to tens of thousands of hard x-ray sources found by BHFP will be an advance similar to the improvement from

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[8] W.N. Brandt and G. Hasinger, 2005, Deep extragalactic x-ray surveys, *Ann. Rev. Astron. Astrophys.* 43:827-859, and references therein.

[9] G. Weidenspointner, C.R. Shrader, J. Knoedlseder, P. Jean, V. Lonjou, N. Guessoum, R. Diehl, W. Gillard, M.J. Harris, G.K. Skinner, P. von Ballmoos, G. Vedrenne, J.-P. Roques, S. Schanne, P. Sizun, B.J. Teegarden, V. Schoenfelder, and C. Winkler, 2006, The sky distribution of positronium annihilation continuum emission measured with SPI/INTEGRAL, *Astron. Astrophys.* 450:1013-1021.

[10] L.M. Winter, R.F. Mushotzky, J. Tueller, C.S. Reynolds, and C. Markwardt, 2007, Early results from Swift's BAT AGN Survey, Presentation Number 002.25, 210th Meeting of the American Astronomical Society, *Bull. Am. Astron. Soc.* 39.

TABLE 2.4 Black Hole Finder Probe (BHFP): Broader Science Examples

Program	Program Characteristics		Program Significance
Galactic 511 keV emission	Science question	Origin of the 511 keV electron-positron annihilation line toward the center of the Milky Way	The universe contains localized sources of antimatter; one set of such sources is indicated by the 511 keV electron-positron annihilation line detected toward the center of the Milky Way. Study of the distribution of the 511 keV sources may indicate whether energetic positrons are produced by extreme physics such as dark matter annihilation or injection by massive cosmic strings.
	Measurements	511 keV line flux vs. position and time in the galactic center direction	
	Quantities determined	Distribution of 511 keV sources toward the center of the Milky Way	
Galactic supernova rate	Science question	Rate of supernova explosions in the Milky Way	Because we live inside the disk of the Milky Way Galaxy, dust extinction makes it difficult to determine the rate of stellar explosions in our Galaxy, which has an impact on theories of cosmic-ray acceleration and other basic astrophysics. BHFP will improve the assessment of the Milky Way supernova rate by measuring the dust-penetrating hard x-ray lines from supernova remnants.
	Measurements	Detection of hard x-ray lines such as the 68 and 78 keV ^{44}Ti lines expected from supernova remnants	
	Quantities determined	Line flux vs. location in the Milky Way; count of associated supernova remnants	
Serendipitous science	Science question	New types of hard x-ray sources revealed by a high-sensitivity survey	BHFP will perform a hard x-ray survey that is more than an order of magnitude more sensitive than any done previously. This new discovery space may enable detection of completely new types of sources, such as extreme magnetars or highly variable ultraluminous x-ray sources.
	Measurements	Hard x-rays and/or rapid variability not associated with known source classes	
	Quantities determined	Identification of new hard x-ray sources with previously unknown types of emitters	

the 300 gamma-ray sources detected by the Compton Gamma-Ray Observatory[11] to the approximately 10,000 gamma-ray sources that will be found by the Gamma-ray Large Area Space Telescope (GLAST) after its launch in late 2007.

A major quest in astrophysics is to understand how galaxies and their constituent components evolve over the age of the universe. Supermassive black holes play a central role in this process through mechanisms not yet fully understood. In order to study this connection, the number, size, and evolution of black holes must first be determined. Although BHFP will not measure the entire black hole population in isolation—many electromagnetic wave bands from radio to infrared to x-ray, as well as gravitational waves, provide signals that may be combined to obtain a complete black hole census—it will provide crucial information on the local obscured population that will not be provided by any other mission. The BHFP contribution to the understanding of this component of galaxies will have broad impact on our knowledge of how black holes form and grow and how they influence the growth and evolution of galaxies.

BHFP also will have significant impact on our knowledge of the population of explosive transients and may well enable the employment of these to probe the transition of the universe from the "dark ages" to the present-day ionized structures. Because of the large detection rate for short transients, BHFP can detect rare events in numbers that will enable us to understand their distribution and frequency. Since many of these events are likely to be binary black hole mergers, the observations can impact knowledge of the event rates for the production of the gravitational radiation that would be detected by LISA and the Laser Interferometer Gravitational Wave Observatory (LIGO). If a sufficient number of bright gamma-ray bursts are detected at high redshift,[12] BHFP localizations combined with ground-based optical follow-up spectroscopy will reveal the chemical enrichment of the universe in the dark ages. Such observations are difficult to make with quasars (which are relatively rare) and are beyond the reach of Type Ia and Type II supernova surveys. These measurements would broadly impact understanding of the evolution of structures, another major objective of modern astrophysics.

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[11] R.C. Hartman, D.L. Bertsch, S.D. Bloom, A.W. Chen, P. Deines-Jones, J.A. Esposito, C.E. Fichtel, D.P. Friedlander, S.D. Hunter, L.M. McDonald, P. Sreekumar, D.J. Thompson, B.B. Jones, Y.C. Lin, P.F. Michelson, P.L. Nolan, W.F. Tompkins, G. Kanbach, H.A. Mayer-Hasselwander, A. Mücke, M. Pohl, O. Reimer, D.A. Kniffen, E.J. Schneid, C. von Montigny, R. Mukherjee, and B.L. Dingus, 1999, The third EGRET catalog of high-energy gamma-ray sources, *Astrophys. J. Suppl. Ser.* 123:79-202.

A unique scientific niche for the BHFP concepts is in the studies of variable hard x-ray sources, including GRBs, x-ray binaries, ultraluminous x-ray sources, magnetars, AGNs, and other potential sources. With the exceptions of the continuing GRB work with Swift and the upcoming GLAST mission, relatively little evolution of knowledge about these variable sources is expected over the next decade. In addition, as stated previously, the opportunity for unexpected discoveries is greatest among the highly variable sources that will be detected by BHFP. This science will not be incremental, but rather it will provide a unique window into the properties and evolution of astronomical objects, the physical processes of which are dominated by strong gravity.

Science Readiness and Risk

It may be quite difficult to make quantitative statements about the growth of black holes in the universe on the basis of BHFP observations. Inferences about black hole masses and their evolution frequently make use of the assumptions that the massive black holes are accreting at or near their Eddington limit and that approximately 10 percent of the mass-energy accreted is turned into radiation. In fact, both assumptions are known to be incorrect in many circumstances. "Starved" black holes may accrete at much less than the Eddington limit due to a paucity of local material, and many active galaxies fall orders of magnitude short of the canonical 10 percent radiative efficiency factor. The black hole at the center of our own Milky Way, as well as the more luminous black holes of low radiative efficiency that reside at the centers of many other galaxies, contradict at least one and possibly both of the standard assumptions for converting x-ray luminosity into a black hole growth rate.[13] Thus, the conversion of a hard x-ray luminosity to a black hole mass or accretion rate could be in error by a factor of 10 or more. As a result, BHFP may enable the derivation of an x-ray luminosity function versus lookback time, but most likely not a black hole mass function versus lookback time.

Another risk factor that could affect the achievement of BHFP science goals is the level of positional accuracy that may be achieved with feasible implementations of coded-aperture imaging. The best accuracies cited by the two candidate missions are 11 arcsec for the EXIST LET and 42 arcsec for the CASTER LEI, roughly calculated as the angular resolution of the instruments (see Table 2.2) divided by the signal-to-noise ratio of the source detection. Experience with deep integrations from the Sub-millimeter Common User Bolometer Array (SCUBA), combined with deep optical images, indicates that there may be several moderate- to high-redshift candidates for the host galaxies of submillimeter sources having approximately 5-15 arcsec position accuracy; only deep centimeter radio images with sub-arcsecond positions have broken the degeneracy in host-galaxy identification.[14] A similar situation may exist for hard x-ray sources in distant galaxies. Thus, BHFP may detect a number of high-redshift black holes but may not be able to identify the host galaxies and determine their redshifts. To fully realize the BHFP scientific potential, it may be important either to improve the source location accuracy to 5 arcsec or better (which is technically quite challenging), or to combine BHFP detections with follow-up observations using a focusing hard x-ray telescope or wide-field infrared and radio surveys.[15] The uncertain availability in the complementary position information during the time frame of BHFP operations is potentially a significant scientific limitation for the presented BHFP mission concepts.

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[12] V. Bromm and A. Loeb, 2006, High-redshift gamma-ray bursts from Population III progenitors, *Astrophys. J.* 642:382-388.

[13] F. Yuan, S. Markoff, and H. Falcke, 2002, A Jet-ADAF Model for Sgr A*, *Astron. Astrophys.* 383:854-863.

[14] R. Ivison, T. Greve, I. Smail, J. Dunlop, N. Roche, S. Scott, M. Page, J. Stevens, O. Almaini, A. Blain, C. Willott, M. Fox, D. Gilbank, S. Serjeant, and D. Hughes, 2002, Deep radio imaging of the SCUBA 8-mJy survey fields: Submillimetre source identifications and redshift distributions, *Mon. Not. R. Astron. Soc.* 337:1-25.

[15] Examples of complementary observations or missions include the Constellation-X Hard X-ray Telescope, the NUSTAR Small Explorer mission, the upcoming Wide-field Infrared Survey Explorer MidEx mission, and the existing Very Large Array survey "Faint Images of the Radio Sky at Twenty cm."

Since the x-ray luminosity thresholds are rather high at high redshifts, it also is important to combine BHFP measurements with sensitive hard x-ray surveys of narrow regions of sky to access the z ~1-2 population over a wider luminosity range. This may be done by combining BHFP information with surveys that could be done by the Con-X Hard X-ray Telescope instrument or by Simbol-X (a proposed hard x-ray focusing mission). Although the continued development of the lanthanum bromide scintillators being studied by the CASTER team may improve high-energy sensitivity, this will not reduce the detection thresholds in the critical band below about 200 keV.

Steps for Moving Forward

Further science planning work, perhaps by the proposing teams, will be important to determine the ancillary observations at other wavelengths that will help in identifying the x-ray sources and then improving their characterization. As noted in the preceding subsection, the conversion from x-ray luminosity to accretion rate has a large uncertainty. Multiwavelength observations of the brighter hard x-ray sources detected by INTEGRAL and Swift and related theoretical developments may lead to better accretion models that will enable an improved conversion from BHFP x-ray luminosities to mass accretion rates. Since multiwavelength information is critical to achieving the primary science objectives, this planning work should be incorporated into the mission at an early stage. Combining the BHFP data with the multiwavelength observations, within a solid theoretical framework, will be necessary for BHFP to realize its full scientific potential.

BHFP was originally proposed as one of the three Einstein Probes in the original Beyond Einstein Program. These missions were envisioned as medium-scale projects that could be executed in less time, and for considerably less money (up to about $600 million), than would be needed for the flagship LISA and Con-X missions. However, the independent assessments produced for the committee estimate that the BHFP probe concepts have costs well above a billion dollars (see the section “Mission Cost Assessments” in Chapter 3). Furthermore, the BHFP candidates are quite massive spacecraft that will require expensive launch vehicles in the Atlas V class. Thus, BHFP costs become a significant factor in the ability to realize most or all of the Beyond Einstein science portfolio. Since BHFP sensitivity scales with the square root of the collecting area, a decrease by a factor of 4 in the detector area would reduce the source-detection threshold by only a factor of 2, with a large savings in detector mass and potential savings in launch vehicle cost. This possible scope reduction should be considered as a means of accelerating the time scale in which BHFP can be implemented. If the predicted masses of the candidate BHFP missions remain near 10,000 kg, a requirement for either BHFP mission to be viable is that the relevant high-capacity launch systems remain available (or be developed) at a reasonable cost for the approximate time frame of a BHFP launch.

Science Assessment Summary

The BHFP concepts presented are both hard x-ray all-sky surveys covering a range from a few kiloelectronvolts to 600 keV. Since massive black holes already are known in many galaxies, finding more such objects would not constitute a revolutionary contribution to Beyond Einstein science. However, detecting the formation of black holes through gamma-ray bursts in the early universe *would* be a revolutionary new discovery of relevance for Beyond Einstein. The science risk for Beyond Einstein is rather high. Although a census of massive black holes in galaxies can be achieved, only very-high-luminosity and very-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. Finally, the difficulty in identifying host galaxies also yields significant risk in the interpretation of BHFP results.

A hard x-ray survey mission such as BHFP will be a unique facility, unmatched by any other space- or ground-based facilities. Thus, it provides an opportunity for the discovery of new types of variable x-ray sources that may relate to the Beyond Einstein Program in unpredictable ways. For example, studies of the power spectra

TABLE 2.5 Black Hole Finder Probe (BHFP): Summary of Scientific Evaluation

	Potential Contributions to Science	
	Beyond Einstein	Broader Science
Factors		
Revolutionary discovery potential	Massive black holes already are known in many galaxies. BHFP may find such black holes in different types of galaxies, where they might not follow the canonical relation between black hole mass and galaxy bulge characteristics. In addition, the possibility of detecting gamma-ray bursts at redshifts higher than 7 could provide insight on the stages of black hole formation in the early universe.	Hard x-ray variability on time scales of milliseconds to days provides the potential for detecting entirely new types of x-ray emitters, such as extreme magnetars or highly variable ultraluminous x-ray sources. In addition, unexpected new classes of sources may be found to be major contributors to the hard x-ray background.
Science readiness and risk	Three major areas of science risk have been identified: (1) BHFP sensitivity is adequate to detect only the most luminous hard x-ray sources at high redshift, making it difficult to infer the evolution of black hole masses or x-ray emission over time; (2) the conversion from x-ray luminosity to black hole growth rate is uncertain by at least an order of magnitude, depending on unknown accretion rates and radiative efficiencies, making the assessment of black hole growth dependent on very poorly constrained models; and (3) the achievable position accuracy may be inadequate to identify the host objects for x-ray sources, particularly at high redshifts.	The likelihood of finding unknown types of variable sources with a significant astrophysical impact is unknown. However, BHFP certainly will measure hard x-ray variability on a variety of time scales that are associated with the evolution of accretion disks and relativistic jets near massive black holes. Although individual supernova remnants will be identified through their hard x-ray spectral lines, these identifications may not translate into a strong constraint on the overall supernova rate in the Galaxy.
Mission Uniqueness		
Versus other space missions	BHFP would perform an all-sky hard x-ray survey a factor of 10 to 100 more sensitive than any previous satellite, detecting approximately 100 times more x-ray-emitting black holes than Swift or INTEGRAL. It will detect several times more gamma-ray bursts than seen by Swift. No other proposed U.S. or international missions will have comparable capabilities.	No other hard x-ray surveys in the past or future have sensitivity and cadence comparable to those of the BHFP, so BHFP has a unique capability to find new types of variable x-ray sources. Further, no missions in prospect have the ability to detect and locate the sources of the 511 keV electron-positron annihilation line as well as the supernova remnant sources of lines in the ~100 keV range.
Versus ground-based instruments	Because of the opaqueness of the atmosphere, no ground-based instrument can perform hard x-ray observations.	No hard x-ray observations are possible from the ground.

NOTE: See Appendix G in this report for definitions of acronyms.

of hard x-ray variability in as many as a thousand massive black holes may enable the direct determination of the black hole masses. Studies of the duty cycles of ultraluminous x-ray sources will allow quantitative studies of the populations of these unusual objects and of the number density of the intermediate-mass black holes that they may represent. BHFP will make significant contributions to several broad science goals by resolving the source(s) of the hard x-ray background and the galactic 511 keV positron-electron annihilation line, as well as identifying new supernova remnants by means of their hard x-ray spectral lines such as ^{44}Ti at 68 and 78 keV (Table 2.5).

CONSTELLATION-X

Introduction

X-ray emission is characteristic of the most violent and energetic objects in the universe, including accreting black holes of all sizes, neutron stars, supernovas and their remnants, events such as gamma-ray bursts associated with the formation of stellar-mass black holes, and mergers of clusters of galaxies. In addition, the gravitational growth of large-scale structure has heated most of the normal matter (baryons) in the universe to high temperatures ($\sim 10^{5\text{-}8}$ K), at which the primary emission and absorption occur in the ultraviolet (UV) and x-ray spectral bands. This intergalactic gas is seen most prominently in the densest regions, clusters of galaxies, where the gas is a particularly hot and bright emitter of x-rays. An advantage of x-rays over some other radiation is that hard x-rays have the property of penetrating significant amounts of matter (hence their use in medical diagnosis), which means that x-rays associated with accretion around black holes can escape from these very dense regions and be observed.

X-ray astronomy began in the late 1940s with the detection of x-rays from the Sun using instruments on sounding rockets.[16] The first detection of extrasolar sources of x-rays occurred in 1962 when a point source of x-rays (Sco X-1) and the diffuse x-ray background were discovered.[17] Early work in x-ray astronomy was limited by the very short exposures possible with sounding rockets. The launch of the Uhuru satellite in 1970 revolutionized the subject, providing a survey of the entire sky and allowing detailed studies of individual sources. X-ray satellites flown during the following 37 years have provided profound insights into the nature of the most energetic objects in the universe. Perhaps the most important instrumental developments have involved the launch of x-ray telescopes with imaging detectors, starting with the Einstein X-ray Observatory, and culminating with Chandra, which has arcsecond angular resolution. Two areas that are ripe for further exploration are very high spectral resolution observations with a sufficiently high throughput to study a wide range of sources, and hard x-ray imaging.

Constellation-X (Con-X) is one of the two Great Observatories within the Beyond Einstein Program.[18] 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 (Tables 2.6 and 2.7). A secondary strength of Con-X is imaging and spectroscopy capability in the hard x-ray region of the spectrum. A single satellite will contain four high-throughput Spectroscopic X-ray Telescopes (SXTs), each equipped with an X-ray Microcalorimeter Spectrometer (XMS), which is an array of nondispersive, high-resolution spectrometers (see Table 2.7). The total collecting area will be about 15,000 cm^2 at a photon energy of 1.25 keV. One or two of the SXTs will also host dispersive X-ray Grating Spectrometers (XGSs), which provide high spectral resolution in the 0.3 to 1 keV band. Con-X will also have one or two Hard X-ray Telescopes (HXTs), which will extend the band-pass up to 40 keV. All of the instruments will operate simultaneously, which increases the observing efficiency and makes it possible to obtain simultaneous spectral information across the 0.3 to 40 keV band for variable objects, such as accreting black holes.

Con-X is a facility-class astronomical observatory. In addition to its key science projects, it will contribute to many other astronomical areas as a result of observations proposed by general observers.

Con-X was rated as the second highest priority among new space observatories (after the James Webb Space Telescope [JWST]) in the previous NRC decadal survey *Astronomy and Astrophysics in the New Millennium*, and was strongly endorsed by the NRC's *Connecting Quarks with the Cosmos* report. The decadal survey said that Con-X "will become the premier instrument for studying the formation and evolution of black holes of all sizes."[19]

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[16] T.R. Burnight, 1949, Soft x-ray radiation in the upper atmosphere, *Phys. Rev.* 76:165; H. Friedman, S.W. Lichtman, and E.T. Byram, 1951, Photon counter measurements of solar x-rays and extreme ultraviolet light, *Phys. Rev.* 83:1025.

[17] R. Giacconi, H. Gursky, F.R. Paolini, and B.B. Rossi, 1962, Evidence for x-rays from sources outside the solar system, *Phys. Rev. Lett.* 9:439.

[18] The Beyond Einstein Great Observatories are major, facility-class missions with broad applications to problems throughout astrophysics and physics, similar in their expected impact to the Hubble Space Telescope and the Chandra X-ray Observatory (National Aeronautics and Space Administration, *Beyond Einstein: From the Big Bang to Black Holes*, Washington, D.C., January 2003, p. 5).

[19] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, p. 11.

TABLE 2.6 Constellation-X (Con-X): Mission Description

Parameter	Value
Primary measurement	X-ray spectroscopy
Observatory type	X-ray telescopes, 0.3-40 keV
Projected years in orbit	>5 yr, with 10 yr of consumables
Type of orbit	L2 halo orbit
Mission phases	One phase, facility-class observatory
Science operations	Guest observer programs with key projects
Other mission characteristics	All instruments operate simultaneously

TABLE 2.7 Constellation-X (Con-X): Mission Instrument Properties

Instrument	Spectral Range (keV)	Spatial Resolution (HPD arcsec)	Spectral Resolution ($E/\Delta E$)	Collecting Area (cm^2)	Field of View ($arcmin^2$)
Microcalorimeter spectrometer—core array	0.3-10	15	2,400 at 6 keV	15,000 at 1.25 keV 6,000 at 6 keV	7
Microcalorimeter spectrometer—outer array	0.3-10	15	300	15,000 at 1.25 keV 6,000 at 6 keV	21
Grating spectrometer	0.3-1	15	1,250	1,000	Not applicable
Hard x-ray telescope	6-40	30	10	150	25

NOTE: HPD, half power diameter.

Connecting Quarks with the Cosmos cited Con-X and LISA as holding "great promise for studying black holes and for testing Einstein's theory in new regimes."[20]

Mission Science Goals

Contribution of the Mission Directly to Beyond Einstein Science Goals

Con-X will test general relativity in the strong field limit by time-resolved spectroscopy of material being accreted just outside the horizon of black holes. The key feature here is high-resolution spectroscopy with high throughput, allowing good time resolution to observe the motions of individual hotspots in the accretion disk. The most useful spectral feature for this capability is the Fe K line, emitted at 6.4 keV.[21] In addition to the motions of individual hotspots, the composite line profiles will be used to determine the spins of the black holes. A wide spectral bandwidth is important for separating the emission lines from the continuum; the hard x-ray capability of Con-X is particularly useful in this regard. A concern with the Con-X test of strong gravity around black holes is that the physics of accretion may turn out to be quite complex, and hotspot accretion disks may not move ballistically. However, Con-X should provide very detailed information on the behavior of accreting matter, thus addressing the last part of the Beyond Einstein Program key question: How do black holes manipulate space, time, and matter? With its very large collecting area, Con-X will allow the study of the evolution of accretion processes over a significant fraction of cosmic time.

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[20] National Research Council, 2003, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., p. 7.

[21] Y. Tanaka, K. Nandra, A.C. Fabian, H. Inoue, C. Otani, T. Dotani, K. Hayashida, K. Iwasawa, T. Kii, H. Kunieda, F. Makino, and M. Matsuoka, 1995, Gravitationally redshifted emission implying an accretion disk and massive black hole in the active galaxy MCG-6-30-15, *Nature* 375:659; T.J. Turner, L. Miller, I.M. George, and J.N. Reeves, 2006, Evidence for orbital motion of material close to the central black hole of Mrk 766, *Astron. Astrophys.* 445:59.

Con-X will also provide at least two measurements of the nature and evolution of dark energy. Both techniques involve the study of clusters of galaxies. Clusters can be used to determine distances (independent of redshift) if one assumes that the gas mass fraction in clusters (essentially, the baryon fraction) is independent of redshift. A geometric measure of dark energy and its evolution comes when these distances are compared to the expansion velocity (redshift).[22] A second type of measurement of dark energy comes from its effect on the growth of structure in the universe. Structure growth will be assessed through observations of the mass distribution function of clusters as a function of redshift. The constraints on dark energy from clusters may be comparably restrictive to those from some other techniques and will have different confidence regions in terms of the relevant cosmological parameters.

Cosmic nucleosynthesis, clusters, and the Wilkinson Microwave Anisotropy Probe (WMAP) provide consistent measurements of the contribution of baryons to the cosmological density. All of the known material (stars, galaxies, gas in galaxies and clusters of galaxies) accounts for less than 40 percent of the baryons expected in the low-redshift universe, however.[23] Cosmological simulations indicate that most of the baryons should be in the form of diffuse intergalactic gas.[24] At low redshifts, this gas is heated by the gravitational growth of structure to temperatures of 10^5 to 3×10^7 K. The intergalactic gas is so diffuse that it would be very difficult to detect in emission. Con-X should be able to detect this Warm-Hot Intergalactic Medium (WHIM) by detecting absorption in the x-ray spectra of AGNs, mainly through the O VII and O VIII x-ray absorption lines. Although most of the mass in the WHIM is in hydrogen and helium, oxygen is the most common heavier element. It may also be possible to detect some of the WHIM by UV absorption measurements in the O VI line with the Cosmic Origins Spectrograph to be installed on the Hubble Space Telescope (HST) during the next servicing mission. However, the bulk of the baryons probably are at higher temperatures and are observable only with x-rays.

Although the scientific projects discussed above and at the top of Table 2.8 represent the core science definition program for Con-X, there are several other research projects that directly address Beyond Einstein science goals. For example, Con-X will study the evolution of supermassive black holes in the universe. Many of the AGNs associated with these objects are optically faint and strongly absorbed, so Con-X's high throughput to hard x-rays will be essential to studying these sources. Also, detailed studies of bright AGNs may lead to a deeper understanding of accretion physics, which would help scientists convert the observed x-ray luminosities of AGNs into more accurate estimates of the growth rates of their supermassive black holes.

Con-X will help to determine the nature of dark matter by mapping the dynamics of clusters of galaxies. It should also detect or strongly limit the masses of sterile neutrinos and other decaying warm dark matter candidates.

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[22] S.W. Allen, R.W. Schmidt, H. Ebeling, A.C. Fabian, and L. van Speybroeck, 2004, Constraints on dark energy from Chandra observations of the largest relaxed galaxy clusters, *Mon. Not. R. Astron. Soc.* 353:457.

[23] M. Fukugita and P.J.E. Peebles, 2006, The cosmic energy inventory, *Astrophys. J.* 616:643.

[24] R. Cen and J.P. Ostriker, 2006, Where are the baryons? II. Feedback effects, *Astrophys. J.* 650:560.

TABLE 2.8 Constellation-X (Con-X): Beyond Einstein Science Programs

Science	Program	Program Characteristics		Program Significance
Science definition programs	Test general relativity in the strong-field limit and measure black hole spins	Science question	Motion near black holes	Does Einstein's theory correctly describe gravity near black holes? Measuring black hole spins will also help to determine how they formed and evolved. The physics of accretion will also be studied.
		Measurements	Observe motion of hotspots in black hole accretion disks	
		Quantities determined	Blob velocities, black hole spins	
	Measure the evolution of dark energy using clusters of galaxies	Science question	What is the nature of dark energy?	Is the dark energy just Einstein's hypothetical cosmological constant or a new force in the universe? Learning how dark energy evolved will tell us about its nature and help predict the future of the universe.
		Measurements	Cluster distance as a function of redshift; cluster abundance evolution	
		Quantities determined	Cluster distances; cluster masses	
	Detect the baryons in the Warm-Hot Intergalactic Medium (WHIM)	Science question	Where are most of the atoms?	Only a small fraction of the atoms in the universe have yet been seen. X-ray absorption should allow us to determine the distribution of most of these thus-far invisible atoms.
		Measurements	Absorption of quasar x-rays by excited oxygen atoms	
		Quantities determined	Amount and metallicity of gas in filaments	
Additional Beyond Einstein science	Evolution of supermassive black holes (SMBHs)	Science question	Relation of SMBH growth to formation of galactic spheroids	SMBH masses are observed to be closely related to those of their host galactic spheroids. Do SMBHs regulate the growth of spheroids or vice versa? How important are mergers vs. accretion in SMBH growth?
		Measurements	X-rays from SMBHs hidden within clouds of gas and dust	
		Quantities determined	X-ray luminosity and attenuation	
	Probing the nature of dark matter	Science question	Does dark matter emit energy via decay or annihilation?	Dark matter constitutes most of the mass of the universe, but we still do not know what it is. Detection of energy inputs from dark matter in clusters could help determine its nature.
		Measurements	Line emission in galaxy clusters	
		Quantities determined	Line energies, luminosities, and widths	

Contribution of the Mission to Other Science

Because Con-X is a facility-class Great Observatory, it is likely that many of the most important scientific contributions of Con-X will be in areas outside those key projects and other Beyond Einstein science mentioned above. Some specific questions are listed in Table 2.9. For example, it has become clear recently that energy input from supermassive black holes helps to regulate the formation of large galaxies and the gas in clusters. Observa-

TABLE 2.9 Constellation-X (Con-X): Broader Science Examples

Program	Program Characteristics		Program Significance
Determine properties of matter at extremely high densities	Science question	Equation of state of neutron stars	Determining the nature of matter within neutron stars will tell us about the strong interaction, and could discover a new state of matter at high density.
	Measurements	X-ray line redshifts and widths	
	Quantities determined	Masses and radii of neutron stars	
Magnetar magnetic fields	Science question	How large are the magnetic fields in young neutron stars?	Magnetars are young neutron stars that are believed to have very strong (~10^{14} G) magnetic fields. These fields can break down the vacuum, and provide a strong test of quantum electrodynamics.
	Measurements	Detect proton cyclotron lines	
	Quantities determined	Magnetic-field strength	
Cosmic feedback from supermassive black holes	Science question	How do supermassive black holes affect galaxies?	The formation of galaxies is strongly affected by energy inputs from the supermassive black holes in galaxy centers.
	Measurements	Measure velocities and densities induced by jets and winds	
	Quantities determined	Velocity, density, kinetic energy input	
Supernovas and the origin of heavy elements	Science question	Where do heavy elements originate?	Heavy elements are made by fusion in stars and dispersed by stellar explosions. Con-X will determine the origin of heavy elements (including some beyond iron) by detecting their x-ray lines in supernova debris.
	Measurements	X-ray emission lines from heavy elements in supernovas and remnants	
	Quantities determined	Abundance of elements	
Stellar activity on Sun-like stars	Science question	How active are Sun-like stars, and how do they affect their environments?	Solar flares and other activity from the Sun affect life on Earth. By observing other similar stars, we can learn about the likely history of the Sun and the effect of stellar activity on forming planetary systems.
	Measurements	X-ray emission and motions in stellar flares and corona	
	Quantities determined	Densities, temperatures, velocities	
Interactions of comets and planets with the solar wind	Science question	How do comets and planets interact with the solar wind?	Observations with ROSAT and Chandra showed that comets and planets emit surprising amounts of x-rays. These occur by interactions with the solar wind.
	Measurements	Line emission by charge exchange	
	Quantities determined	Composition, density, and ionization	

tions with Chandra have provided the first clear information on this feedback;[25,26] high-spectral-resolution x-ray observations with Con-X are important to understanding the detailed physics of all forms of AGN feedback.

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[25] A.C. Fabian, J.S. Sanders, G.B. Taylor, S.W. Allen, C.S. Crawford, R.M. Johnstone, and K. Iwasawa, 2006, A very deep Chandra observation of the Perseus cluster: Shocks, ripples, and conduction, *Mon. Not. R. Astron. Soc.* 366:417; D.A. Rafferty, B.R. McNamara, P.E.J. Nulsen, and M.W. Wise, 2006, The feedback-regulated growth of black holes and bulges through gas accretion and starbursts in cluster central dominant galaxies, *Astrophys. J.* 652:216.

[26] S. Kaspi, W.N. Brandt, I.M. George, H. Netzer, D.M. Crenshaw, J.R. Gabel, F.W. Hamann, M.E. Kaiser, A. Koratkar, S.B. Kraemer, G.A. Kriss, S. Mathur, R.F. Mushotzky, K. Nandra, B.M. Peterson, J.C. Shields, T.J. Turner, and W. Zheng, 2002, The ionized gas and nuclear environment in NGC 3783. I. Time-averaged 900 kilosecond Chandra grating spectroscopy, *Astrophys. J.* 574:643.

Con-X will discover close pairs of orbiting supermassive black holes by detecting pairs of iron K emission lines produced by the Doppler shifts due to the orbital motions.

Con-X will constrain the properties of matter at extremely high densities by determining the masses and radii of neutron stars. These will be determined by measuring the redshifts (z, essentially GM/R) and pressure-broadened widths (g, essentially GM/R^2) of x-ray absorption lines and by pulse shapes during burst oscillations. The masses and radii will constrain the equation of state of ultradense matter in neutron stars and determine the role of exotic phases of matter, such as quark-gluon plasma.

Con-X should be able to detect ion cyclotron lines from magnetars and confirm that these are very highly magnetized neutron stars. The strong fields may provide a unique test of quantum electrodynamics through changes in behavior at the quantum critical magnetic field, which is given by $B = m_e^2 c^3/(\hbar e) = 4.4 \times 10^{13}$ G. However, the complex physics of the x-ray emission mechanisms near magnetars and the possibly complicated magnetic field geometry may make these tests ambiguous.

Con-X should resolve the mystery of the nature of ultraluminous x-ray sources (ULXs) seen in many nearby galaxies. These are x-ray sources that, although not located at the centers of galaxies, have luminosities which are too large to be due to simple accretion by neutron stars or stellar-mass black holes. One theory is that these are binary stars with intermediate-mass (100 to 10,000 solar masses) black holes.

Spectra of supernova remnants and other explosive phenomena will provide important dynamical information on these events. Con-X should give the first measurement of abundances of heavy elements beyond the iron peak and may determine the sites of heavy-element nucleosynthesis.

Con-X would extend the study of stellar coronae, flares, and other stellar activity to other Sun-like stars. Solar activity affects communications and other aspects of life on Earth, and stellar activity may influence the conditions under which planets form.

On the other end of the astronomical spectrum, x-ray spectra of comets and Jovian planets will provide new information on their composition and interactions with the solar wind.

Opportunity for Unexpected Discoveries

Because Con-X is a facility-class general observatory, the probability that it will enable unexpected discoveries is very high. It is important to keep in mind that many of the most important discoveries by Chandra and HST, two previous Great Observatories, were completely unanticipated. (Note that even the first-light image with Chandra of the supernova remnant Cas-A discovered a probable neutron star remnant at its center, which has never been detected in any other waveband.[27])

In addition to the chances for serendipitous discoveries, the general observer program of Con-X will harness the ingenuity of the entire astronomical community. Past experience has shown that many extremely clever and innovative ideas emerge when the entire world of astronomers and physicists has access to an observatory with vastly increased capabilities, such as Con-X.

The recent history of astronomy has shown the great value of multiwavelength observations. High-throughput and high-spectral-resolution x-ray measurements with Con-X will complement observations with the Atacama Large Millimeter Array (ALMA) in the millimeter and submillimeter, the JWST in the infrared, and the large ground-based optical/infrared observatories being planned for the same time period.

It should be noted, however, that x-ray astronomy has become a mature scientific area, and Con-X is not a survey instrument. Thus, Con-X may have less potential than some other missions do for discovering entirely new classes of objects, but it will nevertheless make fundamental contributions to the understanding of currently known phenomena and to basic physics.

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[27] H. Tananbaum, 1999, Cassiopeia A. *IAU Circ.* 7246; G.G. Pavlov, V.E. Zavlin, B. Aschenbach, J. Truemper, and D. Sanwal, 2000, The compact central object in Cassiopeia A: A neutron star with hot polar caps or a black hole? *Astrophys. J.* 531:L53.

Assessment of Scientific Impact

Overall Assessment

Revolutionary Nature of the Science Although the capabilities of Con-X represent an evolution of x-ray satellite technology and it is not a survey instrument, its very large collecting area and high-resolution spectrometry capability could lead to fundamental discoveries. The science goals for Con-X include tracing baryonic matter in the WHIM, determining the mass and radius of neutron stars and the mass and spin of stellar-mass black holes, studying the formation and evolution of supermassive black holes (SMBHs) and their roles in galaxy and cluster formation, and measuring cosmological parameters using clusters of galaxies. Con-X could find potentially revolutionary surprises in any of these areas—for example, discovery of a new state of matter deep in neutron stars or deviations from the expected Kerr metric around black holes. However, interpreting any of these potential observations may be complicated because of the complex physics involved.

Precision Measurement of Fundamental Quantities The best opportunity to make a precision measurement of a fundamental quantity is probably the determination of the dark energy equation-of-state parameter w by measuring the growth in the number of clusters of given mass as redshift decreases. There is no question that Con-X will enable greatly improved measurements of temperature, metallicity, and other properties of clusters. However, the interpretation of these measurements is likely to be somewhat uncertain, since clusters are complex. Cosmological dark matter simulations determine the number density of clusters of a given mass accurately as a function of cosmological parameters, but the challenge is to determine cluster masses accurately from observable quantities. While theory is improving, there are still serious difficulties in understanding cluster energy input and its consequences. In particular, the energy input from the growth of SMBHs is likely to be important in explaining the absence of cooling flows in low-redshift clusters and in preventing the overcooling of baryons at higher redshifts. The nature and timing of such energy inputs and how the energy couples to the cluster baryons remain uncertain, and one of the key advances from Con-X observations would be to help answer these questions. It is possible that the improved theoretical understanding of clusters will indeed enable a high-precision measurement of w, but the level of attainable precision is difficult to estimate at present.

Another way that Con-X could improve the measurement of w is to measure the distance to clusters independent of their redshifts, assuming that the cluster baryon fraction is independent of redshift. The open question here is whether the uncertainties will be small enough to be competitive with other methods. However, it is important to measure fundamental quantities by several independent methods that have different sources of uncertainty, and the methods using clusters are quite different from the other methods being pursued using supernovas, weak lensing, and baryon acoustic oscillations.

Advances in Basic Astrophysics Unquestionably, Con-X would advance astrophysics on a broad front. Besides its science drivers—testing strong-field general relativity, determining the dark energy parameter w, and observing WHIM—Con-X will provide important new information on many other key astrophysical questions. Its unprecedented spectral capabilities and high-energy x-ray sensitivity will allow Con-X to clarify the evolution of SMBHs and their role in the evolution of galaxies and clusters. Con-X can detect close SMBH binaries by means of their spectra. It can also constrain the nature of dark matter and clarify how heavy elements are formed. It can determine the nature of the ULXs that have recently been detected in nearby galaxies; the presence of relativistic iron K-shell lines and the variability time scales could solidify the interpretation of these observations as intermediate-mass black holes (IMBHs). And Con-X could also improve the understanding of flares on the Sun and nearby stars and could probe the magnetospheres of the Jovian planets in our solar system and the composition of comet comas.

Breadth of the Science Impact It should be clear that Con-X would have an extremely broad impact on astrophysics and beyond. Its observations of magnetars could test quantum electrodynamics in the strong-magnetic-field regime, and new data on dark matter properties could be a significant new input for fundamental particle physics.

But the main impact of the Con-X would be to extend the enormous progress of x-ray astronomy by enabling high-spectral-resolution measurements of a wide range of phenomena.

Context of Science and Mission

Unique Capabilities Con-X will be unique. Given its roughly two-order-of-magnitude increase in spectral resolution and collecting area, no other existing x-ray observatory can match its high-throughput spectral capability.

Complementary Role with Other Missions The large ground-based optical telescopes such as the W.M. Keck Observatory's twin 10-m-diameter telescopes and the Very Large Telescope (VLT) have complemented the high angular resolution of HST with high-resolution optical spectrometry. If Con-X is active during the period when new instruments such as ALMA and JWST are available, the opportunities for complementary measurements will be increased, since the universe is relatively transparent to submillimeter, infrared, and x-ray photons that these instruments will observe. For example, JWST observations and Con-X x-ray spectra could together characterize the AGN population out to high redshift, while ALMA and Con-X could determine the role of obscured AGNs in submillimeter-bright galaxies. Thirty-meter-class ground-based optical telescopes are expected to begin operating within about a decade, and Con-X would also complement these instruments, for example, by measuring galaxy outflow winds driven by starbursts and AGNs.

Can the Science Questions Be Answered by Other Space Missions and/or by Ground-Based Capabilities? Some of the science questions that Con-X will address (e.g., the nature and evolution of dark energy, or the structure of spacetime near black holes) can be addressed by other missions. In these cases, it would still be valuable to make these measurements in several different ways. In addition, many of the science questions that Con-X will address, including the nature of dark matter in clusters and detecting the majority of baryons in intergalactic gas, require x-ray observations. Since x-rays do not penetrate the atmosphere, it is essential to put x-ray telescopes in space. The other proposed international x-ray telescope that may most closely match or exceed Con-X capabilities is the European X-ray Evolving Universe Spectroscopy (XEUS) mission; however, projected European Space Agency (ESA) funding would not permit XEUS to be started for perhaps a decade. Japan's New X-ray Telescope (NeXT) mission, with a possible launch in about 2013, would cover roughly the same hard x-ray energies as are covered by the Con-X HXT, but with an effective area at least an order of magnitude smaller, poorer angular resolution, and a smaller field of view, limiting it to the study of only the brightest sources.

Science Readiness and Risk

Risks to Achieving Science Goals

With the foundations laid by Chandra and X-ray Multi-Mirror Mission-Newton (XMM-Newton), the field of x-ray astronomy has become quite mature. These previous observatories have provided information on thousands of sources. As mentioned earlier, Con-X represents an evolution in technology through high spectral resolution and throughput. These advances will enable a number of high-science-return measurements on known sources. For example, the high throughput will allow sensitive measurements of time-varying sources critical to the study of compact objects.

Aside from the well-known risks of satellite implementation, a number of technical risks have been identified by the Con-X team, as discussed in detail in Chapter 3. Other than these technical risks, the science risks are moderate to low. As discussed above, the most significant science risks are associated with the possible physical complexity of the systems (accretion disks around black holes, clusters of galaxies) that will be used to probe strong gravity and dark energy.

Required Enabling Science

The time and spectral resolution capabilities of Con-X stand alone in the study of black hole properties.

In order to constrain the evolution of dark energy using clusters of galaxies, Con-X will require larger samples of high-redshift clusters than currently exist. However, it is very likely that such samples will be available before they are needed, as a result of Planck or ground-based Sunyaev-Zeldovich surveys, or from x-ray detections with current observatories or the extended Roentgen Survey with an Imaging Telescope Array (eROSITA). Although these surveys will provide high-redshift cluster samples, the high throughput and spectral resolution of Con-X will be needed to determine the cluster properties accurately enough for strong dark energy evolution constraints. Con-X will be able to observe far more clusters than Chandra or XMM-Newton can. The ~15 arcsecond resolution provided by Con-X will allow for some discrimination of merging and otherwise complex clusters from the relaxed clusters to be used for measuring dark energy parameters. However, it is likely that even higher resolution imaging of the clusters at other wavelengths will be required to fully achieve the stated dark energy goals.

Finding the missing baryons by measuring absorption features on background continuum sources in the WHIM is a very powerful tool enabled by Con-X. The target AGNs for this measurement have already been identified to allow the detection of approximately 100 filaments. There are no other measurements needed to achieve this goal. However, continued modeling of the expected measurements will certainly help to make the best use of observing time.

Evolution of Knowledge Versus Potential Mission Start

The field of x-ray astronomy is defined by the current and planned missions. At the present time and for the period leading up to a Con-X deployment, the state of the art in x-ray astronomy is determined by Chandra and XMM-Newton data. Consequently, the state of the field at the start of the mission is easy to predict. While other missions will continue to make progress, the capabilities of Con-X will yield a significant step in the x-ray field. The only caveat to this is the potential of instrumental technology advances that would go beyond the Con-X stated goals.

Steps for Moving Forward

Con-X is one of the best-studied missions in the Beyond Einstein Program. Because of this high level of development, the committee's suggestions for moving forward are more focused than for some of the less-developed missions. The Technology Readiness Levels (TRLs) of the key components of Con-X are in the TRL 3-5 range (in Chapter 3, see the section entitled "Technology Readiness and Degree of Difficulty" for the definition of TRLs). This high level of pre-Phase A readiness can be attributed to the heritage of the flight technology, strong community participation and support, and, finally, to the availability of significant resources for technology and mission development. All of the components have strong heritage with previous missions, most notably Chandra and XMM-Newton. The team has produced a large volume of studies to back up its plans to bring these components to flight status.

The committee notes that the technological requirements to achieve the mission goals appear to have been purposely kept conservative. The positive side is that the path to achieving the requirements (such as an angular resolution of ~15 arcsec) is well defined. The significant progress achieved both at the laboratories and by university-based groups indicates that a more aggressive influx of resources in key areas such as the mirror development, the staged cooler system, and the large microcalorimeter arrays would be of significant benefit to developments in these areas.

Science Assessment Summary

The primary strength of Con-X, one of the two Great Observatories included in the Beyond Einstein Program, is the ability to carry out x-ray astronomy with very high spectral resolution and high throughput, representing

TABLE 2.10 Constellation-X (Con-X): Summary of Scientific Evaluation

	Potential Contributions to Science	
	Beyond Einstein	Broader Science
Factors		
Revolutionary discovery potential	Measure growth of structure and distance-redshift relation using clusters—revolutionary if $w \neq -1$. Test general relativity in strong fields by measuring motions in accretion disks around black holes.	Discovery of exotic phases of matter in neutron stars—e.g., quark-gluon plasma. Potential discovery of small-separation orbiting supermassive black holes. Test of quantum electrodynamics in strong magnetic fields with magnetars.
Science readiness and risk	Unclear whether definitive measurement of cosmological parameters is possible using clusters due to complex gas physics. Interpretation of data on accretion disk motion may be difficult.	Complex physics may make interpretation of data difficult.
Mission Uniqueness		
Versus other space missions	Detecting the bulk of baryons in the warm-hot intergalactic medium.	The high-throughput, high-resolution capabilities of Con-X ensure that it will make unique and broad contributions to astrophysics.
Versus ground-based instruments	X-ray astronomy can only be done from space.	X-ray astronomy can only be done from space.

an improvement of two orders of magnitude over current missions. It will make the broadest and most diverse contributions to astronomy and physics of any of the Beyond Einstein missions. It also has the potential to make very strong contributions to Beyond Einstein science. However, other missions address the measurement of dark energy parameters and tests of strong-field general relativity in a more focused and definitive manner. A summary of the committee's evaluation of the scientific merit of Con-X within the Beyond Einstein Program is given in Table 2.10. However, given the very strong, very broad contribution that Con-X will make to basic astrophysics, the committee concluded that its merits 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.

INFLATION PROBE

Introduction

Inflation, the term for an era of early universe exponential expansion, has been proposed as a solution to several fundamental problems in cosmology. Among these is the "Horizon Problem," the difficulty that apparently causally disconnected regions appear to have almost identical conditions, as though they had been in thermal contact. Another is the "Flatness Problem," the fact that the universe appears to be very close to being geometrically flat despite the fact that it should evolve away from flat as the universe expands.[28] Inflation also naturally explains the generation of "seeds" of structure formation from quantum fluctuations and predicts a nearly scale-free power spec-

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[28] A. Guth, 1981, Inflationary universe: A possible solution to the horizon and flatness problems, *Phys. Rev. D.* 23:347.

TABLE 2.11 Inflation Probe (IP): Mission Description

Parameter	CMB Polarization	CIP
Primary measurement	CMB B-mode Survey	Hα galaxy survey
Observatory type	Millimeter telescope	Passively cooled slitless grating spectrograph
Projected years in orbit	1	3
Type of orbit	L2 or IRAS/COBE	L2 or IRAS/COBE
Mission phases	One phase, full-time scanning	One phase, full-time scanning
Science operations	Full-time scanning	Full-time scanning
Other mission characteristics	Cryogenic	

NOTE: See Appendix G in this report for definitions of acronyms.

TABLE 2.12 Inflation Probe (IP): Mission Instrument Properties

Instrument	Spectral Range	Spatial Resolution	Spectral Resolution ($\nu/\delta\nu$)	Collecting Area	Field of View
EPIC-F	30-300 GHz	0.25-2.5 degrees	3	0.4 m^2	5 degrees
CMBPol	30-300 GHz	1 degree	3	0.2 m^2	~15 degrees
EPIC-I	30-250 GHz	1 degree	3	0.002-0.1 m^2	7 degrees
CIP	2.5-5 μm	0.2 arcsec	600	2.54 m^2	20 arcmin

NOTE: See Appendix G in this report for definitions of acronyms.

trum ($P(k)$).[29] During the inflationary era the universe expanded by 30 orders of magnitude in linear scale, creating nearly all of the particles and radiation in the current universe. Evidence for a flat universe is very well established experimentally.[30,31] More recently the power spectrum slope of the cosmic microwave background (CMB) has been measured with high precision and is, as expected, close, but possibly not exactly, scale invariant.[32] The Inflation Probe (IP) seeks to study the conditions that existed during this crucial phase in the history of the universe. Its objectives are challenging, since direct observational connections with this early era are difficult to find.

Four proposed missions in the Beyond Einstein Program fall under the "Inflation Probe" title. Three are aimed at learning about the inflationary period using the signal imparted to the polarization of the CMB radiation by gravitational waves induced during the inflationary period. The fourth mission measures the structure in the universe on various length scales, which arises from the primordial density fluctuations induced by the inflation potential. The polarization mission concepts are CMB Polarimeter (CMBPol), the Experimental Probe of Inflationary Cosmology (called EPIC-F below, because it is a filled aperture telescope), and the Einstein Polarization Interferometer for Cosmology (called EPIC-I below, since it is an interferometric experiment). The polarization missions are collectively designated "CMB polarization," while the power spectrum mission is referred to as the Cosmic Inflation Probe (CIP).

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[29] J.M. Bardeen, P.J. Steinhardt, and M.S. Turner, 1983, Spontaneous creation of almost scale-free density perturbations in an inflationary universe, *Phys. Rev. D.* 28:679.

[30] P. de Bernardis, P.A.R. Ade, J.J. Bock, J.R. Bond, J. Borrill, A. Boscaleri, K. Coble, B.P. Crill, G. De Gasperis, P.C. Farese, P.G. Ferreira, K. Ganga, M. Giacometti, E. Hivon, V.V. Hristov, A. Iacoangeli, A.H. Jaffe, A.E. Lange, L. Martinis, S. Masi, P. Mason, P.D. Mauskopf, A. Melchiorri, L. Miglio, T. Montroy, C.B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, S. Prunet, S. Rao, G. Romeo, J.E. Ruhl, F. Scaramuzzi, D. Sforna, and N. Vittorio, 2000, A flat universe from high-resolution maps of the cosmic microwave background radiation, *Nature* 404:955.

[31] D.N. Spergel, L. Verde, H.V. Peiris, E. Komatsu, M.R. Nolta, C.L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S.S. Meyer, L. Page, G.S. Tucker, J.L. Weiland, E. Wollack, and E.L. Wright, 2003, First-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters, *Astrophys. J. Suppl. Ser.* 148:175.

[32] D.N. Spergel, R. Bean, O. Doré, M.R. Nolta, C.L. Bennett, J. Dunkley, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H.V. Peiris, L. Verde, M. Halpern, R.S. Hill, A. Kogut, M. Limon, S.S. Meyer, N. Odegard, G.S. Tucker, J.L. Weiland, E. Wollack, and E.L. Wright, 2006, Wilkinson Microwave Anisotropy Probe (WMAP) three year results: Implications for cosmology, *Astrophys. J. Suppl. Ser.* 170:377.

There are two types of CMB polarization patterns: E-modes, produced both during and after inflation by electron scattering, and B-modes, generated by small distortions in the E-mode pattern either from gravitational waves or gravitational lensing. The E-mode polarization has been detected with the predicted characteristics by several experiments.[33,34] Tables 2.11 and 2.12 list the mission and instrument characteristics of the four IP mission concept studies. The importance of these measurements was detailed in the NRC report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*[35] and the joint National Science Foundation (NSF)/NASA/Department of Energy (DOE) CMB Taskforce report.[36]

Mission Science Goals

Contribution to Beyond Einstein Science Goals

Each of the proposed Inflation Probe concepts will test the existence and properties of inflation. They are expected to shed light on the specific Beyond Einstein question, What powered the big bang? Specifically, the gravitational waves measured by the polarization missions will determine the magnitude of the potential during inflation, while the matter power spectrum measured by CIP gives information about the shape of the potential.

In addition, understanding the accelerating expansion during the inflationary era might help to understand the dark energy that is causing the current acceleration of the expansion.

The more detailed statement of the Beyond Einstein goal on what powered the big bang sets forth the goal of searching for gravitational waves from inflation and phase transitions in the big bang. While this statement indicates that the authors of the Beyond Einstein roadmap were expecting that the Inflation Probe would be a CMB polarization mission, the Cosmic Inflation Probe also seems relevant to the more general Beyond Einstein goal in the 2003 roadmap. Table 2.13 lists the Beyond Einstein science that would be performed by the four mission concepts.

Observations of the polarization of the CMB can distinguish between different models of the early universe. The critical signal is the B-mode polarization of CMB fluctuations, imprinted on the CMB by gravitational waves generated by inflation. The B-mode amplitude is proportional to the energy density during inflation. If the inflationary model is correct, the successful detection of large-angular-scale B-mode polarization in the CMB produced by gravitational waves from inflation will therefore measure the energy scale of inflation.[37]

As inflation ends, the energy density declines, locking in the shape of the power spectrum of primordial density fluctuations. The shape of the potential function for the inflation fields can be constrained by precise measurements of the spectral index (or slope) and curvature (or running) of the fluctuation power spectrum.[38] This well-understood technique has already been implemented with the CMB temperature fluctuations at large angular scales and surveys such as the Sloan Digital Sky Survey (SDSS). The CIP project proposes to substantially improve the knowledge of these quantities.

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[33] E.M. Leitch, J.M. Kovac, N.W. Halverson, J.E. Carlstrom, C. Pryke, and M.W.E. Smith, 2004, DASI Three-year cosmic microwave background polarization results, *Astrophys. J.* 624:10.

[34] A. Kogut, D.N. Spergel, C. Barnes, C.L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, M. Limon, S.S. Meyer, L. Page, G.S. Tucker, E. Wollack, and E.L. Wright, 2003, First-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Temperature-polarization correlation, *Astrophys. J. Suppl. Ser.* 148:161-173.

[35] National Research Council, 2003, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C.

[36] R. Weiss, J. Bock, S. Church, M. Devlin, G. Hinshaw, A. Lange, A. Lee, L. Page, B. Partridge, J. Ruhl, M. Tegmark, P. Timbie, B. Winstein, and M. Zaldarriaga, 2005, *Task Force on Cosmic Microwave Background Research: Final Report*, available at http://www.nsf.gov/mps/ast/tfcr_final_report.pdf.

[37] M. Kamionkowski and A.H. Jaffe, 2001, Detection of gravitational waves from inflation, *Int. J. Mod. Phys. A* 16:116-128.

[38] M. Takada, E. Komatsu, and T. Futamase, 2006, Cosmology with high-redshift galaxy survey: Neutrino mass and inflation, *Phys. Rev. D* 73:83520.

TABLE 2.13 Inflation Probe (IP): Beyond Einstein Science Programs

Science	Program	Program Characteristics		Program Significance
Science definition programs	All-sky CMB polarization map (CMB polarization)	Science question	Detect gravitational waves sourced by inflation	The inflation model of the early universe predicts two types of fluctuations: density perturbations that evolve into structure, and tensor or gravitational perturbations. The ratio of the amplitude of the two perturbations is a measure of the energy scale of inflation.
		Measurements	All sky CMB B-mode polarization study	
		Quantities determined	Gravitational-wave amplitude and energy scale of inflation	
	2.5-5.5 μm galaxy redshift survey at $z = 3$ to 5 using H-alpha line (CIP)	Science question	Constrain the physics of inflation	Models of inflation and what drives it have distinct predictions for the matter fluctuation power spectrum. An accurate measure of the spectrum constrains the possible inflation mechanisms. CIP when combined with CMB constraints significantly narrows the possible inflation models.
		Measurements	Measure the galaxy power spectrum at scales ranging from the CMB to optical galaxy surveys	
		Quantities determined	Power spectrum slope from 5 to 500 h^{-1} Mpc	
Additional Beyond Einstein science	Baryonic oscillations at high redshift (CIP)	Measurements	Detect baryonic oscillations in the matter power spectrum	The properties of dark energy can be probed using geometry. The baryon acoustic oscillations have a known scale. Measuring their angular size at redshift of 3-5 will constrain the properties of dark energy.
		Quantities determined	Angular diameter distance $3 < z < 5$	
		Science question	Dark energy properties	

NOTE: See Appendix G in this report for definitions of acronyms.

Contributions of the Mission to Other Science

Two kinds of mission have been proposed as Inflation Probes, and their contributions to other science differ. The CMB polarization experiments will need to achieve a very good understanding of the magnetic field in the Milky Way and the properties of interstellar dust. Thus, the CMB polarization experiments will contribute substantially to both the study of galactic magnetic fields and to the study of the properties of interstellar grains. The E-mode polarization at large angular scales will also provide information about the history of reionization. The scattering of CMB photons by free electrons can only produce E-mode polarization, and WMAP has detected the large-angular-scale E-mode polarization produced since the universe was reionized 400 million years after the big bang. The Inflation Probe would provide a much higher signal-to-noise ratio and would be able to study the time history of the reionization of the universe.

The Cosmic Inflation Probe studies galaxies at high redshift. It will generate a very large catalog of high-redshift emission-line galaxies, which will aid in understanding the assembly of galaxies and the star-formation history of the universe. This catalog will provide many interesting targets for follow-up studies with the JWST. In addition, the experiment is sensitive to the growth of structure on scales from 10 to 1,000 megaparsecs (Mpc). Questions that can be touched on with concurrent CMB and nearby Large-Scale Structure (LSS) surveys are the neutrino mass, dark energy constraints, galaxy clustering properties, and galaxy evolution. Table 2.14 lists the broader science capabilities of the missions.

Opportunity for Unexpected Discoveries

CIP's high-redshift LSS survey provides many possibilities for unexpected discoveries. It will catalog 10^7 high-redshift galaxies, providing unprecedented information about the star-formation history of the universe. The catalog

TABLE 2.14 Inflation Probe (IP): Broader Science Examples

Program	Program Characteristics		Program Significance
Polarized galactic foreground (CMB polarization)	Science questions	What is the nature of galactic dust, galactic magnetic fields, electron spectrum?	The types of emission from galactic dust are not known. The distribution of grain sizes and temperature will be better determined with polarized measurements through the submillimeter wavelength range. The nature of high galactic latitude dust will be characterized.
	Measurements	Polarization of galactic emission	
	Quantities determined	Dust grain properties, dust thermal environment, global maps of galactic magnetic fields	
Ionization history of the universe (CMB polarization)	Science question	When was the universe reionized?	Energy injected into the universe by the formation of the first massive stars caused it to become reionized. The redshift of the epoch is an important detail in understanding the evolution of structure.
	Measurements	E-mode polarization of the CMB	
	Quantities determined	Total optical depth to scattering of CMB photons in the nearby universe. Possibly some constraints on the reionization history.	
High-redshift star formation rate (CIP)	Science question	What is the history of star formation for $3 < z < 6$?	The star formation rate in early galaxies is uncertain. How galaxies formed and how and when they generated the elements that we see are not yet known.
	Measurements	Measure the star formation rate in 10^7 galaxies $3 < z < 6$	
	Quantities determined	Not applicable	
Neutrino mass (CIP)	Science question	What are the masses of the three kinds of neutrinos?	Neutrinos are now known to have masses. The differences between the mass squared of types of neutrinos are known, but the actual masses have not yet been determined.
	Measurements	The matter power spectrum from 1,000 to $5\ h^{-1}$ Mpc is sensitive to the neutrino masses.	
	Quantities determined	The total mass of all neutrinos to a 2σ level of 0.05 eV	

NOTE: See Appendix G in this report for definitions of acronyms.

will serve as a target list for JWST and other instruments. The CMB experiments with beams larger than 1 degree have fewer chances for unexpected discoveries, since they will have been preceded by WMAP and Planck.

Mission Characteristics

Three of the four Inflation Probe missions measure the B-mode CMB radiation polarization. B-modes have a twistiness or handedness that cannot be produced by the polarization dependence of electron scattering and are generated only in the presence of spatial distortions arising from either gravity waves or gravitational lensing. This signal is generated by gravitational waves with wavelengths on the order of the speed of light times the age of the universe and from gravitational lensing on much smaller scales. Processes occurring during the CMB emission do not generate B-mode polarization. The B-mode signal is generated subsequently as the photons travel through the spacetime distorted by the gravitational waves. The signal from inflation is strongest at angular scales of several degrees, and, because of reionization, the B-mode signal can also be seen at scales greater than 20 degrees, though the amplitude depends on the optical depth due to electron scattering that occurred after reionization. Instruments designed to make this B-mode measurement must have sensitivity about a factor of 10 better than any current measurement. Even more challenging is the required rejection of foreground signal from the galaxy[39] and the required rejection of leakage of temperature and E-mode polarization signal into the B-mode signal.[40] All three CMB polarization missions address these requirements and their challenges.

Experimental Probe of Inflationary Cosmology The EPIC-F is a cryogenic, bolometric instrument with angular resolution of about 1 degree operating at frequencies from 30 to 300 GHz. It employs six 30 cm telescopes, each at a different frequency band, with a total of 830 bolometers. The angular resolution scales with wavelength. The probe operates at the second Earth-Sun Lagrange point (L2) for a year. This mission will use a phased array of slot antennas coupled to transition edge sensor (TES) bolometers. This planar detector technology is to be tested in proposed and ongoing ground-based and balloon instruments in the next 5 to 10 years. The focal plane array is more compact than an array of horns with the same number of detectors. This detector system, though still untested in real observational situations at this time, will likely be more mature by the close of this decade.[41]

Einstein Polarization Interferometer for Cosmology EPIC-I is a Fizeau interferometric instrument operating in a 900-km-altitude polar orbit with an operating lifetime of 1 year. The synthesized beam resolution is 1 degree in all bands, and the instrument uses 1,024 detectors. The proposed system could be made with either bolometric or amplified detector systems. The proposed interferometric technique, which may offer immunity to some types of systematic errors, requires extensive field and flight testing before it could be considered for a space mission. In addition, this team has not yet selected between bolometric and heterodyne sensors. In either case, considerable development is needed to integrate the detectors with the interferometer system. At this time, no specific projects are in development that will test the Fizeau interferometric technique in a full-scale astronomical instrument.

CMBPol CMBPol is a general mission concept for measuring CMB polarization at large angular scales. The proposed concept would fly in a Cosmic Background Explorer (COBE) 900-km-altitude polar orbit using about 1,000 bolometers covering 6 bands from 30 to 300 GHz and having about a 1 degree resolution. The mission concept study discusses foreground removal, polarization techniques, and the choice of orbit. A candidate detector system using an array of horn-fed waveguide planar ortho-mode antennas is presented. This detection system requires a very large field of view. The system has not yet been used in an astronomical measurement but a balloonborne system using this technology is in development.[42]

Cosmic Inflation Probe CIP will generate a 140 square degree survey of galaxies at redshift from 3 to 6.5 in Hα emission. The goal is to measure the primordial power spectrum at spatial scales smaller than is possible with CMB anisotropy. Together with both low-redshift surveys and high-quality CMB anisotropy information, CIP provides tight constraints on inflation models. The mission consists of a 1.8 meter cooled telescope with a slitless grating spectrometer with resolution of 600, operating at wavelengths from 2.5 to 5 micrometers. The mission would operate at the Sun-Earth L2 Lagrange point for 3 to 5 years.

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[39] M. Tegmark, D.J. Eisenstein, W. Hu, and A. de Oliveira-Costa, 2000, Foregrounds and forecasts for the cosmic microwave background, *Astrophys. J.* 530:133.

[40] W. Hu, M.M. Hedman, and M. Zaldarriaga, 2003, Benchmark parameters for CMB polarization experiments, *Phys. Rev. D* 67:043004.

[41] C.L. Kuo, J.J. Bock, G. Chattopadthyay, A. Goldin, S. Golwala, W. Holmes, K. Irwin, M. Kenyon, A.E. Lange, H.G. LeDuc, P. Rossinot, A. Vayonakis, G. Wang, M. Yun, and J. Zmuidzinas, 2006, Antenna-coupled TES bolometers for the SPIDER experiment, *Nucl. Instrum. Methods A* 559:608.

[42] A. Kogut, D.T. Chuss, D. Fixsen, G.F. Hinshaw, M. Limon, S.H. Moseley, N. Phillips, E. Sharp, E.J. Wollack, K. U-Yen, N. Cao, T. Stevenson, W. Hsieh, M. Devlin, S. Dicker, C. Semisch, and K. Irwin, 2006, PAPPA: Primordial Anisotropy Polarization Pathfinder Array, *New Astron. Rev.* 50:1009.

Assessment of Scientific Impact

Overall Assessment

Revolutionary Nature of the Science The question of the nature of the inflationary era is most assuredly fundamental. The initial conditions for all the subsequent evolution were set during inflation or are a direct consequence of the physics of inflation. The Inflationary Big Bang Model predicts that the expansion was propelled by a quantum mechanical vacuum energy. A better understanding of this era will help to answer the question, What powered the big bang?

Advances in Basic Astrophysics The inflationary era generated the seed fluctuations for the long period of structure growth that followed. A fundamental understanding of the nature and spectrum of the fluctuations would underpin our knowledge of the structure formation processes.

Breadth of Science Impact Models of inflation explain the largest structures in the universe in terms of quantum fluctuations and phenomena at the smallest scales. Physics and astronomy are both tied directly to an understanding of the inflationary period. The Inflation Probe is the next step along the path to that understanding. The accelerating expansion that occurred during inflation may have a connection to the accelerating expansion occurring today because of the presence of dark energy. A deeper understanding of inflation and dark energy is needed to explore that similarity.

Context of the Science and Mission

Unique Capabilities Very few observational probes exist to verify and characterize inflation. The inflationary scenario was inspired by cosmological observations that indicated in a very indirect way that something was amiss in the then-current picture of the early universe. But the problems with the standard big bang model were subtle, and the development of the theory of inflation followed the observational facts by more than a decade. With the introduction of the Inflation Probe missions, some of the few direct observational predictions of inflation can be tested. In view of the fundamental nature of the idea of inflation, these predictions should be explored as soon as possible.

Complementary Role with Other Missions The study of the early universe involves the fusion of many research paths. These include past, present, and future missions such as COBE, WMAP, and Planck. The interpretation of the results from any of the IP missions will depend on and complement the results from these prior efforts. In addition, major ground-based and suborbital work is under way to fill in the technological, observational, and theoretical gaps that will be required to fully realize the potential of the Inflation Probe.

Can the Science Questions Be Answered by Other Space Missions and/or Ground-Based Capabilities? Since the angular scale of the B-mode signal from inflation is on the order of a few degrees or more, ground-based experiments are unlikely to be able to provide the highest signal-to-noise ratio, systematic-error-free power spectra. Atmospheric emission, emission from warm optics, and ground emission are all difficult observational problems that have yet to be demonstrably overcome at the needed levels of sensitivity. While the Planck mission is space-based, the scan pattern is not optimized for large-angular-scale polarization measurements and may compromise the large-angle polarization fidelity. Ground-based and balloonborne experiments are important stepping-stones toward the detection of B-mode polarization. They are likely to be the first to detect the B-mode signal from gravitational lensing of the CMB at smaller angular scales, but such observations do not probe inflation.

CIP will extend precision measurements of the galaxy power spectrum by about a factor of 5 higher in wave number. This range of wave numbers is covered by ground-based measurements of galaxy clustering and the Lyman-alpha forest, but the corrections for nonlinear structure growth have prevented an accurate determination of the primordial power spectrum using these data. The development of an accurate nonlinearity correction for

Lyman-alpha forest data could reduce the value of CIP data. WMAP data plus current galaxy data from the SDSS have already made a preliminary measurement of the power spectrum spectral index. Planck will improve the data in the low-wave-number region currently covered by WMAP, leading to a severalfold improvement beyond current knowledge of the power spectrum. Adding CIP data to Planck plus SDSS data will yield another severalfold improvement in the determination of the power spectrum.

Science Readiness and Risk

Science Readiness

Risk to Achieving Science Goals The theoretical framework for understanding the results of both the CMB and high-redshift galaxy observations exists. The observations will fit readily into models of the universe and provide useful constraints on cosmological parameters.

Required Enabling Science The polarization missions will need to extract a B-mode signal, which is a factor of 30 below the estimated signal from galactic foregrounds. Extensive research into the characterization and modeling of polarized galactic emission will be required to mitigate this mission risk.

Science Risk

One concern about the B-mode polarization experiments is based on the fact that the B-mode power varies as the fourth power of the energy scale during inflation, so there is only a factor of 3 range in energy scale between the current limits on the B-mode power and the likely detection limits of the Inflation Probe.[43] Possibly mitigating this concern is the fact that—for the current best estimates for the spectral index of the primordial power spectrum—the energy scale for inflation may be in this range for typical inflation models. The CIP proposes to measure this spectral index to much greater precision. However, there are other inflation models in which the B-mode power is disconnected from the spectral index.

Steps for Moving Forward

The CMB polarization Inflation Probes collectively are in an early stage of development. The three proposals outline detector and instrument concepts that are extrapolations from existing experiments. No detailed engineering or budgeting plans have been presented. No instrument focal planes of the complexity or sensitivity proposed are in operation on any platform.

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. The polarization, stability, and characterization of the instrument needed to achieve a successful B-mode spectrum measurement are at levels far beyond what has been reached with currently existing instruments. EPIC-F proposes to use doped germanium resistance thermometers in bolometers that are very similar to the detectors in Planck. The committee's assessment of the TRLs for EPIC-F are discussed in Chapter 3 and range from TRL 3 to 6+ for various components. A successful Planck mission will go much of the way, but not all the way, toward proving the readiness of the detector technology. The EPIC-I and CMBPol concepts were less detailed, and they contemplate using detectors that have less heritage and have not been developed for spaceflight. The committee did not have enough information to assess the TRL of CMBPol and EPIC-I. Further support of detector and ultracool cryocoolers (sub-100 mK) is needed to push these missions along. The three CMB missions have proposed three different approaches for modulating the polarization signal to separate the desired polarized signal from the much larger temperature anisotropy. Ground-based and balloonborne demonstrations of these techniques would be a cost-effective way to demonstrate these techniques.

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[43] A. Amblard, A. Cooray, and M. Kaplinghat, 2007, Search for gravitational waves in the CMB after WMAP3: Foreground confusion and the optimal frequency coverage for foreground minimization, *Phys. Rev. D* 75:083508.

The CIP concept is mature, and much of the design for the mission is a modification of existing missions. The detectors are very similar to the JWST Near-Infrared Camera (NIRCAM) long-wavelength detectors, but CIP requires eight times as many detectors as NIRCAM. While there may be a need for further theoretical advances to obtain the most from the mission, there are no major hurdles to overcome in order to start the mission.

Impacts on Institutional Relationships

None of the missions proposed here involves partnerships outside of NASA. Thus, the impacts of either a 2009 start or a deferred start on relationships with NSF, DOE, or ESA are minimal.

TABLE 2.15 Inflation Probe (IP): Summary of Scientific Evaluation

	Potential Contributions to Science	
	Beyond Einstein	Broader Science
Factors		
Revolutionary discovery potential	Knowing the energy scale is crucial for understanding inflation (CMB polarization). Improved measurement of spectral index and running constrains the shape of the inflationary potential (CIP).	Interstellar dust and galactic magnetic-field properties interesting to a small community (CMB polarization). Large IR spectroscopic survey will find many unusual and interesting objects that will be good targets for JWST (CIP).
Science readiness and risk	The energy scale of inflation could be outside the 3× range, between the current limit and the foreground subtraction limit. Foreground subtraction could be too difficult (CMB polarization). Improved understanding of nonlinearities in $P(k)$ and/or the Lyman-alpha forest could reduce the value of the result (CIP).	Low risk, since foreground signal will be strong (CMB polarization). Low risk, since such a large spectroscopic survey will certainly find many fascinating sources such as high-z quasars (CIP).
Mission Uniqueness		
Versus other space missions	The Big Bang Observer (follow-on to LISA) could measure the gravitational waves from inflation (CMB polarization). Other large-scale spectroscopic surveys such as ADEPT could duplicate some CIP science. Planck will also improve our knowledge of the spectral index, but in a different part of the spectrum (CIP).	Planck will provide information on the galactic magnetic fields and interstellar dust, but not the large-angular-scale B-modes (CMB polarization). Objects in similar classes could be found in other large-scale spectroscopic surveys, but missions such as ADEPT will not duplicate CIP bands and fields of view (CIP).
Versus ground-based instruments	Ground-based experiments are unlikely to measure the large-angular-scale B-modes from inflation (CMB polarization). SKA, MWA, and LOFAR could measure $P(k)$ at high z using high-redshift 21 cm spectra. Ground-based spectroscopic surveys will improve on the SDSS measurement of $P(k)$ (CIP).	Ground-based (and balloon) experiments could measure IS dust properties and B-modes from lensing (CMB polarization). Sensitive measurements in CIP band are not possible from the ground (CIP).

NOTE: See Appendix G in this report for definitions of acronyms.

Science Assessment Summary

The Inflation Probe has a diverse set of mission concepts, using two very different types of observations to probe two quite different aspects of the vacuum energy density or potential that powered inflation. The CMB polarization mission concepts seek to measure the absolute level of the potential, while the high-redshift galaxy power-spectrum mission concept seeks to measure the shape (normalized derivatives) of this potential. The CMB polarization is very difficult to measure; doing so requires unprecedented detector sensitivity and foreground rejection accuracy, but it will provide a unique view of the inflationary era. These CMB mission concepts require continued technology development and the acquisition of more data about the galactic foreground (Table 2.15). ESA's Planck mission and ongoing ground-based and balloonborne CMB polarization experiments will provide both platforms for testing technology and more foreground data. The galaxy power-spectrum measurement improves on existing data by a factor of about 5, limiting its revolutionary science potential, but it is technically ready to proceed.

THE JOINT DARK ENERGY MISSION

Introduction

NASA and DOE are developing the Joint Dark Energy Mission primarily to investigate the dark energy of the universe. Three mission concepts were considered by the committee: the Supernova Acceleration Probe (SNAP), the Dark Energy Space Telescope (DESTINY), and the Advanced Dark Energy Physics Telescope (ADEPT). The committee reviewed each of these candidate missions in order to evaluate the potential scientific impact of JDEM, with the understanding that the eventual JDEM mission resulting from a request for proposals could be one of these three, or a mission based on a different combination of techniques.

Each of the proposed JDEM candidates is based on an optical-to-near-infrared wide-field survey telescope. SNAP is a 1.8 m telescope concept with 0.7 square-degree field of view and optical and near-IR (NIR) imaging, plus spectroscopy and multiband photometry capability for the study primarily of Type Ia supernovas and weak lensing. DESTINY is a proposed 1.65 m telescope designed for near-IR spectrophotometry of high-redshift supernovas and for weak lensing with multiband photometry. ADEPT would employ a 1.3 m telescope operating in the near-IR focusing on baryon acoustic oscillations as well as Type Ia supernovas. Each of these missions would be capable of high-precision studies of dark energy out to redshifts on the order of 1.7. A brief description of the mission and a listing of the instrument properties are provided in Tables 2.16 and 2.17.

TABLE 2.16 Joint Dark Energy Mission (JDEM): Mission Description

Parameter	Value
Primary measurement	Optical/near-IR imaging and spectroscopy
Observatory type	Optical/near-IR wide-field survey telescope
Projected years in orbit	3-yr primary, 5-yr goal
Type of orbit	LEO (ADEPT); L2 (DESTINY/SNAP)
Mission phases	ADEPT: full-sky survey DESTINY: 24 months SN survey, 12 months weak-lensing survey SNAP: 22 months SN survey, 12 months weak-lensing survey
Science operations	Continuous survey

NOTE: See Appendix G in this report for definitions of acronyms.

TABLE 2.17 Joint Dark Energy Mission (JDEM): Mission Instrument Properties

Instrument	Spectral Range (microns)	Spatial Resolution (arcsec)	Spectral Resolution ($\lambda/\Delta\lambda$)	Collecting Area (diameter in meters)	Field of View (sq. deg)
SNAP imager	0.35-1.7	0.14	5	1.8	0.7
SNAP spectrometer	0.35-1.7	0.14	100 (visible) 70 (NIR)	1.8	Not applicable
DESTINY imager	0.85-1.7	0.15	5	1.65	0.12
DESTINY grism	0.85-1.7	0.15	75	1.65	0.12
ADEPT slitless spectrograph	1.3-2.0	Not available	Not available	1.3	Not available

NOTE: See Appendix G in this report for definitions of acronyms.

Mission Science Goals

Over the past decade, conclusive evidence has been assembled indicating that the expansion of the universe is accelerating.[44–50] Within the standard cosmological model, this expansion implies that some 70 percent of the mass-energy density of the universe is in the form of a mysterious dark energy that counters the attractive gravitational force of matter and radiation. The accelerating expansion of the universe is one of the great discoveries in the history of cosmology, and it could have profound implications for elementary particle physics, general relativity, and astronomy.

JDEM will address one of the central questions of the Beyond Einstein Program: What is the mysterious dark energy pulling the universe apart? Little is known at present about dark energy. Whether dark energy is due to a cosmological constant term in Einstein's equation for general relativity, a dynamically evolving quantum field, a modification of general relativity, or some other new physics cannot be determined from the data currently available. To explore the nature of dark energy, JDEM must determine to high precision whether the accelerating expansion is consistent with a cosmological constant, or whether the dark energy density is evolving with time. Comparison

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[44] A.G. Riess, A.V. Filippenko, P. Challis, A. Clocchiattia, A. Diercks, P.M. Garnavich, R.L. Gilliland, C.J. Hogan, S. Jha, R.P. Kirshner, B. Leibundgut, M.M. Phillips, D. Reiss, B.P. Schmidt, R.A. Schommer, R.C. Smith, J. Spyromilio, C. Stubbs, N.B. Suntzeff, and J. Tonry, 1998, Observational evidence from supernovae for an accelerating universe and a cosmological constant, *Astron. J.* 116:1009.

[45] S. Perlmutter, G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P.G. Castro, S. Deustua, S. Fabbro, A. Goobar, D.E. Groom, I. M. Hook, A.G. Kim, M.Y. Kim, J.C. Lee, N.J. Nunes, R. Pain, C.R. Pennypacker, R. Quimby, C. Lidman, R.S. Ellis, M. Irwin, R.G. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B.J. Boyle, A.V. Filippenko, T. Matheson, A.S. Fruchter, N. Panagia, H.J.M. Newberg, and W.J. Couch, 1999, Measurements of omega and lambda from 42 high-redshift supernovae, *Astrophys. J.* 517:565.

[46] D.N. Spergel, L. Verde, H.V. Peiris, E. Komatsu, M.R. Nolta, C.L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S.S. Meyer, L. Page, G.S. Tucker, J.L. Weiland, E. Wollack, and E.L. Wright, 2003, First-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters, *Astrophys. J. Suppl. Ser.* 148:175.

[47] D.N. Spergel, R. Bean, O. Doré, M.R. Nolta, C.L. Bennett, J. Dunkley, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H.V. Peiris, L. Verde, M. Halpern, R.S. Hill, A. Kogut, M. Limon, S.S. Meyer, N. Odegard, G.S. Tucker, J.L. Weiland, E. Wollack, and E.L. Wright, 2007, Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Implications for cosmology, *Astrophys. J. Suppl. Ser.* 170:377.

[48] A.G. Riess, L.-G. Strolger, S. Casertano, H.C. Ferguson, B. Mobasher, B. Gold, P.J. Challis, A.V. Filippenko, S. Jha, W. Li, J. Tonry, R. Foley, R.P. Kirshner, M. Dickinson, E. MacDonald, D. Eisenstein, M. Livio, J. Younger, C. Xu, T. Dahlén, and D. Stern, 2007, New Hubble Space Telescope discoveries of Type Ia supernovae at $z \geq 1$: Narrowing constraints on the early behavior of dark energy, *Astrophys. J.* 659:98.

[49] D.J. Eisenstein, I. Zehavi, D.W. Hogg, R. Scoccimarro, M.R. Blanton, R.C. Nichol, R. Scranton, H.-J. Seo, M. Tegmark, Z. Zheng, S.F. Anderson, J. Annis, N. Bahcall, J. Brinkmann, S. Burles, F.J. Castander, A. Connolly, I. Csabai, M. Doi, M. Fukugita, J.A. Frieman, K. Glazebrook, J.E. Gunn, J.S. Hendry, G. Hennessy, Z. Ivezi, S. Kent, G.R. Knapp, H. Lin, Y.-S. Loh, R.H. Lupton, B. Margon, T.A. McKay, A. Meiksin, J.A. Munn, A. Pope, M.W. Richmond, D. Schlegel, D.P. Schneider, K. Shimasaku, C. Stoughton, M.A. Strauss, M. SubbaRao, A.S. Szalay, I. Szapudi, D.L. Tucker, B. Yanny, and D.G. York, 2005, Detection of the baryon acoustic peak in the large-scale correlation function of SDSS luminous red galaxies, *Astrophys. J.* 633:560.

[50] W.J. Percival, S. Cole, D.J. Eisenstein, R.C. Nichol, J.A. Peacock, A.C. Pope, and A.S. Szalay, 2007, Measuring the Baryon Acoustic Oscillation scale using the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey, *Mon. Not. R. Astron. Soc.* 381:1053-1066.

of the effect of dark energy on the expansion history of the universe with its effect on the history of the growth of structure will address both the nature of dark energy and the correctness of general relativity.

The wide-field optical-NIR surveys required for exploring dark energy will also produce data sets of unprecedented richness for the investigation of a very broad range of other astrophysical questions.

Contribution of the Mission Directly to Beyond Einstein Goals

JDEM will probe the nature of dark energy by measuring its effects on the expansion history of the universe and on the history of the growth of structure. Several observational techniques exist for the exploration of dark energy. The report of the Dark Energy Task Force (DETF),[51] established by the Astronomy and Astrophysics Advisory Committee (AAAC) and the High Energy Physics Advisory Panel (HEPAP), discussed four techniques:

1. Supernova (SN) surveys use Type Ia supernovas as standard candles to determine the luminosity distance versus redshift relation.
2. Weak lensing (WL) surveys measure the bending of light as it passes galaxies or galaxy clusters. WL is sensitive to dark energy through dark energy's effect on the growth rate of structure.
3. Baryon acoustic oscillations (BAOs) are observed through surveys of the spatial density and distribution of galaxies. This technique is sensitive to dark energy through dark energy's effect on the angular-diameter distance versus redshift relation.
4. Galaxy cluster (CL) surveys measure the distances, distribution, and spatial density of clusters. CL is sensitive to dark energy through the angular-diameter distance versus redshift relation and the growth rate of structure.

The use of two or more of these techniques provides improved sensitivity and important cross-checks. Furthermore, as discussed in the Dark Energy Task Force report,[52] a comprehensive dark energy program should provide measures of both the homogeneous (geometric) and inhomogeneous (growth of structure) effects of dark energy, in order to provide the potential to test whether an acceleration of expansion arises from the modification of general relativity. It is also important to have both types of tests, especially when considering that a simple parameterization of dark energy may be incomplete. Each of the proposed JDEM concepts would employ at least two of the first three techniques. DESTINY and SNAP would rely equally on supernovas (a geometric test) and weak lensing (both a geometric test and a growth-of-structure test). ADEPT would rely mainly on baryon acoustic oscillations (a geometric test), and also includes a study of supernovas. The galaxy cluster technique would be employed by Con-X.

A principal goal with each observational technique is to measure accurately the ratio of the dark energy pressure P to its energy density ρ, $w(a) = P(a)/\rho(a)$, as a function of the scale factor $a = 1/(1 + z)$ (where z is redshift), or equivalently as a function of time. If the presence of a cosmological constant term in general relativity (GR) is an accurate model for dark energy, then the energy density is uniform in space and constant in time, and $w = -1$ for all times. If instead, a dynamical field is responsible for the dark energy, then w could take on other values and vary with time. The Dark Energy Task Force adopted a simple, two-parameter description of $w(a)$, and defined a figure of merit for its measurement in terms of the inverse area of the 95 percent confidence-limit ellipse in the space of these two parameters. The task force called for a factor-of-10 gain over current accuracy in this figure of merit for any JDEM-generation dark energy project, a somewhat arbitrary but not unreasonable goal for advancing the understanding of dark energy.

ADEPT would determine the expansion history of the universe using a full-sky spectroscopic survey that measures baryon acoustic oscillations derived from redshifts and positions of approximately 100 million galaxies

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[51] A. Albrecht, G. Bernstein, R. Cahn, W.L. Freedman, J. Hewitt, W. Hu, J. Huth, M. Kamionkowski, E.W. Kolb, L. Knox, J.C. Mather, S. Staggs, and N.B. Suntzeff, 2006, *Report of the Dark Energy Task Force*, available at http://arxiv.org/ftp/astro-ph/papers/0609/0609591.pdf.

[52] A. Albrecht, G. Bernstein, R. Cahn, W.L. Freedman, J. Hewitt, W. Hu, J. Huth, M. Kamionkowski, E.W. Kolb, L. Knox, J.C. Mather, S. Staggs, and N.B. Suntzeff, 2006, *Report of the Dark Energy Task Force*, available at http://arxiv.org/ftp/astro-ph/papers/0609/0609591.pdf, Section IX, pp. 53-78.

TABLE 2.18 Joint Dark Energy Mission (JDEM): Beyond Einstein Science Programs

Science	Program	Program Characteristics		Program Significance
Science definition programs	SNAP and DESTINY	Science question	What is the nature of dark energy?	Combining SN light curves with WL results will provide a measure of the expansion rate of the universe to ~1%. This level will provide over a factor-of-10 improvement compared to the current knowledge of the dark energy contribution and may establish that dark energy does not arise from a cosmological constant, that it varies dynamically with time, or that it arises from a modification of general relativity.
		Measurements	Light curves of Type Ia supernovas (SN) with $0.3 < z < 1.7$ via deep-field survey of 3-7.5 sq. deg; gravitational WL via wide-field survey of 1,000-4,000 sq. deg	
		Quantities determined	Expansion history of the universe; history of growth of structure	
	ADEPT	Science question	What is the nature of dark energy?	ADEPT combines BAOs with SN light curves to provide a measure of the expansion rate of the universe to approximately 1%. This level will provide over a factor-of-10 increase compared to the current knowledge of the dark energy contribution and may establish that dark energy does not arise from a cosmological constant or that it varies dynamically with time.
		Measurements	Baryon acoustic oscillations (BAOs) derived from redshifts and positions of 100 million galaxies with $1 < z < 2$ and light curves of Type Ia SN with $0.8 < z < 1.3$ via a full-sky spectroscopic survey	
		Quantities determined	Expansion history of the universe	

NOTE: See Appendix G in this report for definitions of acronyms.

with redshifts in the range $1 < z < 2$ and that measures light curves of approximately 1,000 Type Ia supernovas with redshifts in the range $0.8 < z < 1.3$. Combining these measurements, ADEPT would determine the expansion rate of the universe to approximately 1 percent, providing at least a factor-of-10 improvement compared to current knowledge. This level of improvement may reveal that dark energy does not arise from a cosmological constant or that it varies dynamically with time. Given the very large volume surveyed and given that the BAO signal is quite free from systematic errors, the measurements of ADEPT should be very robust.

SNAP or DESTINY would determine the expansion history of the universe by way of a deep-field survey of 3-7.5 square degrees that measures light curves of Type Ia supernovas with redshifts in the range $0.3 < z < 1.7$. They would also determine the expansion history and the history of the growth of structure through a wide-field survey of 1,000-4,000 square degrees that measures gravitational weak lensing of galaxies. Combining these measurements, either of these missions would determine the expansion rate of the universe to approximately 1 percent, providing at least a factor-of-10 improvement in accuracy over current measurements. This level of improvement, along with measurement of the histories of both expansion and growth of structure, may reveal that dark energy does not arise from a cosmological constant, that it varies dynamically with time, or that it arises from a modification of general relativity.

A brief summary of the Beyond Einstein science goals of each of the proposed JDEM concepts is provided in Table 2.18.

Contribution of the Mission to Other Science

Dark energy manifests itself only on large scales; consequently, any JDEM mission will probe large volumes of space, which will naturally lead to a substantial observational data set that can be used to address a significant range of astrophysics questions. This broader science program of JDEM will appeal to many astrophysicists. A brief summary of some examples of the broader science goals of each of the proposed JDEM concepts is provided in Table 2.19. An imaging survey, such as DESTINY or SNAP, would provide a large, deep survey in multiple

TABLE 2.19 Joint Dark Energy Mission (JDEM): Broader Science Examples

Program	Program Characteristics		Program Significance
SNAP and DESTINY	Science question	How did galaxies form and evolve?	After HST there will be no large diffraction-limited optical or near-IR telescope in space. The low background and large field of views offered by SNAP and DESTINY will provide the most detailed and important information ever for understanding how galaxies formed and acquired their mass.
	Measurements	Photometric surveys in 5 (DESTINY) to 9 (SNAP) optical and NIR bands	
	Quantities determined	Deep-field survey over 3 sq. deg (DESTINY) to 7.5 sq. deg (SNAP); wide-field survey over 1000 sq. deg (DESTINY) to 1,000-4,000 sq. deg (SNAP)	
ADEPT	Science question	At what rate did stars form, and how did that rate depend on environment?	There has never been a full-sky spectroscopic survey from space; consequently, ADEPT has large discovery potential. It will characterize the star formation rate of the universe down to a sensitive limiting flux, finding the most extreme star-forming galaxies in the universe. The epoch that ADEPT probes is the most active when galaxies acquire their mass. Very little is known about star formation in the smallest galaxies.
	Measurements	Full-sky IR spectroscopic survey	
	Quantities determined	Redshift and emission fluxes for over 100 million galaxies	

NOTE: See Appendix G in this report for definitions of acronyms.

bands. A spectroscopic survey, such as ADEPT, would provide a full-sky survey of the near-IR emission-line universe. Large-scale surveys have had substantial impact on basic astrophysics in the past. For instance, SDSS,[53,54] which has been operating since 1998 and whose survey was recently extended, has resulted in many hundreds of publications with many thousands of citations. The scientific impact of such surveys typically extends well beyond their initial goals.

The significant potential impact of JDEM imaging studies would derive from the very wide and deep fields that they image. Requirements for dark energy studies using weak lensing demand a very-wide-field survey, typically at least 1,000 square degrees, and requirements for dark energy studies using supernovas demand multiple images of a wide field, typically 15 square degrees, that provide a very-deep-field survey. For example, the SNAP supernova survey would cover an area of 7.5 square degrees, 2,000 times larger than the Hubble Ultra-Deep-Field (HUDF) survey,[55] and deeper in each of nine color bands from optical through NIR wavelengths. It would reach much greater depths than SDSS. The SNAP weak-lensing survey would cover an area of 1,000 (4,000 in the full extended mission) square degrees, at least 500 times larger than the Cosmological Evolution Survey (COSMOS)[56] field and to similar depth. DESTINY would provide similar results.

Significant impact of a JDEM imaging study would also derive from enhanced sensitivity in the NIR relative to present and future ground-based surveys. Such sensitivity would allow studies such as those currently under way with SDSS to be extended to the high-redshift universe. A large imaging survey such as DESTINY and SNAP would greatly complement the exquisite detail obtained from HST wide-field camera WF3 and JWST.

The benefits of deep optical and NIR images are easily seen from the advances made with HST. Understanding how galaxies form, acquire their mass, and evolve has been a prime focus of HST studies. The low-background,

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[53] D.G. York, J. Adelman, J.E. Anderson, Jr., S.F. Anderson, J. Annis, N.A. Bahcall, J.A. Bakken, R. Barkhouser, S. Bastian, E. Berman, W.N. Boroski, et al., 2000, The Sloan Digital Sky Survey: Technical summary, *Astron. J.* 120:1579.

[54] J.K. Adelman-McCarthy, M.A. Agüeros, S.S. Allam, K.S.J. Anderson, S.F. Anderson, J. Annis, N.A. Bahcall, I.K. Baldry, J.C. Barentine, A. Berlind, M. Bernardi, et al., 2006, Fourth data release of the Sloan Digital Sky Survey, *Astrophys. J. Suppl. Ser.* 162:38.

[55] S.V.W. Beckwith, M. Stiavelli, A.M. Koekemoer, J.A.R. Caldwell, H.C. Ferguson, R. Hook, R.A. Lucas, L.E. Bergeron, M. Corbin, S. Jogee, N. Panagia, M. Robberto, P. Royle, R.S. Somerville, and M. Sosey, 2006, The Hubble Ultra Deep Field, *Astron. J.* 132:1729.

[56] N. Scoville and the COSMOS Survey Group, 2007, Large scale structure in COSMOS, 210th Meeting of the American Astronomical Society, Presentation Number 039.01, *Bull. Am. Astron. Soc.* 39.

high-spatial-resolution images have been invaluable for quantifying morphology, which has been the major obstacle for ground-based studies. A data set that is over three orders of magnitude larger than that obtained from HST will allow a direct comparison with ground-based studies (present and future) of the nearby universe. A JDEM imaging survey, such as DESTINY or SNAP, would dominate the studies of how galaxies acquire their mass over time, reaching back through more than 90 percent of the age of the universe, from redshift zero to ~3.5.

Data from JDEM imaging surveys would enable a wide range of other astrophysical studies in addition to studies of galaxy evolution and morphology. For example, with a deeper field and near-infrared capability, the unobscured quasar luminosity function could be mapped to $z \sim 10$, far beyond the $z < 6$-6.5 range of SDSS and the planned Dark Energy Survey (DES). With identification of high-redshift quasars and galaxies, the era of reionization could be probed in great detail, and, in combination with spectroscopic studies from the ground or JWST, measurements of the proximity effect and the spatial structure of reionization could be performed. Imaging data would also enable studies of stellar populations, distributions, and evolution. Exploiting near-infrared capabilities of the imaging studies would also enable a census of nearby low-mass L and T stars and brown dwarfs in the Milky Way. Faint, cool objects in the outer solar system could also be discovered in the time series data of the imaging studies. The imaging studies would also provide important information and identification of targets such as quasars, galaxies, and gamma-ray bursts for JWST. With large imaging surveys and repetitive pointing on the same fields, a JDEM mission such as DESTINY or SNAP would have significant potential for unexpected discoveries.

A spectroscopic near-infrared JDEM survey would also offer significant discovery potential. For instance, ADEPT would produce a full-sky slitless-grism survey at moderate resolution. Its spectral range is 1-2 microns, corresponding to various emission lines over redshifts of $0.8 < z < 8$, or higher. This redshift range is one of the most important for studies of star formation, because it is during those eras that most stars formed. Having a flux-limited spectrographic survey with no selection effects is essential to an understanding of where stars are formed and the processes that control star formation. Such a survey would find the most prolific star-forming objects in the universe and the pure emission-line objects, allowing the most robust measure of where stars are formed.

By providing the largest-effective-volume survey of the universe, a full-sky, spectroscopic JDEM survey such as ADEPT would perform studies of many phenomena in addition to star formation. For instance, it could be used to measure the power spectrum of density fluctuations, to study high-order n-point correlation functions, to improve the determination of matter density, and for high-statistics studies of active galactic nuclei. Such a full-sky, spectroscopic survey has never been obtained; consequently, such a JDEM survey also offers significant potential for unexpected discoveries.

A JDEM infrared imaging or spectroscopic large-format telescope could also prove invaluable in locating infrared transients associated with LISA signals indicating imminent supermassive black hole mergers.

Thus, as a secondary but potentially equally important contribution to science, JDEM will produce an extraordinary database that, properly archived and made available to the community in a timely manner after acquisition, would provide the basis for a broad archival research program leading to opportunities for unexpected discoveries in many areas of astrophysics. The broader science potential of JDEM has been critical to the high urgency that the committee has assigned to JDEM, and developing this potential will continue to have great value regardless of which JDEM mission concept may be selected.

Opportunity for Unexpected Discoveries

In summary, JDEM will offer the opportunity for unexpected discoveries both through its dark energy measurements and through its broader science program. By performing a precision study of the expansion history of the universe, JDEM will provide the possibility for unexpected, fundamental discoveries regarding the nature of dark energy. JDEM may establish that the expansion rate is consistent with a cosmological constant, or may alternatively discover that the history of expansion demands the existence of a new dynamical field or that it demands modification of the theory of general relativity. Such a discovery would be profound. Furthermore, in order to achieve the sensitivity required for its studies of dark energy, JDEM would establish an astrophysical reach greatly beyond that of present surveys. The rich data set from its large field survey—whether it be the wide-field and deep-field photometric imaging surveys of a JDEM mission such as DESTINY or SNAP or the full-sky spectroscopic survey of a mission such as ADEPT—would enable not only the broad program of astrophysical studies sketched above, but it would also open a window for new exploration and unexpected discoveries.

Assessment of Scientific Impact

Broad Science Impact

The history of the expansion of the universe reflects the nature of the fundamental principles that govern the expansion. Recent studies have conclusively demonstrated that the universe is expanding ever more rapidly, rather than slowing because of the pull of gravity. Within the standard cosmological framework, the observed acceleration of expansion must be caused by an unknown entity, dark energy, that behaves as if it has negative pressure and that comprises 70 percent of the mass-energy of the universe. JDEM will perform precision studies of the history of expansion, shedding light on the nature of dark energy that will shape our understanding of gravity and the theories of fundamental particles and fields and of general relativity. Indeed, the present mystery of dark energy demonstrates that our current theories are incomplete or incorrect. Probing dark energy through astrophysical observations that enable the precision measurement of expansion is essential to progress in the understanding of these theories that are the foundation of our understanding of nature on both the largest and the smallest scales.

Advances in Basic Astrophysics

JDEM will advance basic astrophysics in several ways. Charting the history of the expansion of the universe is a basic astrophysical measurement that has been a mainstay of astrophysics since the work of Edwin Hubble in the early part of last century. Furthermore, JDEM's wide-field surveys will provide a wealth of data over unprecedented areas. This data sample will enable new measurements on many key astrophysical questions, for instance on galaxy formation and evolution using a photometric imaging survey, as proposed by SNAP and DESTINY, or on star formation using a spectroscopic survey, as proposed by ADEPT. A deep-field photometric survey, as proposed by SNAP and DESTINY, would also provide deep-field data over unprecedented areas.

Precision Measurement

The primary goal of JDEM, to deepen the understanding of dark energy and the accelerating expansion of the universe through precision measurement, may lead to revolutionary science. JDEM will measure fundamental properties, characterized by variables such as $w(a)$, at an unmatched level of precision—possibly even illuminating the source of dark energy. Such a result would be a major advance in basic astrophysics and cosmology and would have broad impact across all of fundamental physics. JDEM's measurements will certainly shape future dark energy research.

Scientific Context

While present observational results from ground and space have revealed the existence of dark energy by determining that the expansion of the universe is accelerating, these results are not capable of distinguishing among the possible explanations of dark energy. Ongoing projects relevant to dark energy are also unlikely to distinguish successfully among the possible explanations, and, if dark energy is not a cosmological constant, will not distinguish among possible dynamical models. Increased observational sensitivity will be needed. Numerous observational projects are being developed, both near-term ground-based projects and longer-term projects on the ground and in space, for example, JDEM. Much research is also being invested in developing new techniques for measuring the effects of dark energy. Using its figure of merit to characterize sensitivity to dark energy parameters, the Dark Energy Task Force projected that near-term projects taken in combination may improve the figure of merit by a factor in the range of approximately 3 to 5 beyond the ultimate results of ongoing experiments, whereas DETF projected that JDEM could be capable of improving the figure of merit by at least a factor in the range of approximately 10 to 15. Proposed future large-scale ground-based observational projects, such as an optical Large Survey Telescope (LST), or eventually a radio Square Kilometer Array (SKA), might also be capable of an order-of-magnitude improvement in the DETF figure of merit. However, projections of the sensitivities for ground-based projects are considerably more uncertain than for JDEM. Much work on observational techniques has ensued since the DETF report, and proponents both of near-term projects and of JDEM concepts and other longer-term projects target improvements better than those projected by the DETF. The ultimate sensitivity of future experiments will depend largely on the capability of the experiments to control systematic uncertainties. The inability to forecast today the level of systematic uncertainties in future experiments gives rise to the ranges in the DETF projections. As part of its study, DETF included a careful discussion of ground- and spaced-based systematics for the four techniques listed above: BAOs, CL formation, Type Ia SNs, and WL.[57] The projected improvements in sensitivity can only be achieved if systematic uncertainties can be adequately controlled, which is generally felt to be easier for a space-based mission such as JDEM.

Systematic uncertainties are biasing effects arising from the environment, the methods of observation, or the instruments employed. Exploration of dark energy by any observational technique may be limited by systematic uncertainties, as future projects will greatly improve statistical samples. The sources of systematic uncertainty differ among techniques. Sources can generally be categorized as observational or astrophysical, where observational uncertainties are intrinsic to the technique and astrophysical uncertainties are intrinsic to the astronomical objects (supernovas or galaxies) used by the technique. Spectroscopic BAO studies are less affected by observational uncertainties than other techniques are; however, they may be limited by two astrophysical uncertainties: nonlinear effects in the growth of structure and understanding of the difference (bias) between the distribution of galaxies and the distribution of matter. Photometric baryon acoustic oscillation surveys may also be limited by bias in the photometric redshift scale, an observational uncertainty. Galaxy cluster surveys may be limited by knowledge of the relationship between galaxy-cluster mass and observables used for the selection of clusters of galaxies, which has both observational and astrophysical contributions. Supernova surveys may be limited by wavelength-dependent errors in the astronomical flux scale, an observational uncertainty, or by any redshift dependency of properties, such as intrinsic luminosity, of supernovas or their host extinction that is not understood and corrected—an astrophysical uncertainty. Surveys using the WL technique, which is not as developed as BAO and SN techniques, may be limited by both observational and astrophysical uncertainties. Limiting weak-lensing observational uncertainties may be miscalibration of the shear measurement as a function of redshift, bias in the photometric redshift scale, and effects of optics and anisotropies in the point-spread function of the optics. Limiting weak-lensing astrophysical uncertainties may arise from inaccuracy of the theoretically calculated power spectrum of dark matter and from intrinsic correlations of galaxy shapes with each other and local density.

All dark energy experiments must limit systematic uncertainties. Space-based experiments, such as JDEM, are generally held to have better control of systematic uncertainties. By virtue of being space-based, JDEM will be able to reduce significantly systematic uncertainties with better angular resolution and using a wider spectrum of diagnostic data for supernova, weak lensing, and/or galaxy cluster surveys than is possible from the ground. Furthermore, JDEM capabilities in the NIR could strengthen constraints on dark energy parameters by studying supernovas and weak lensing of galaxies at higher redshifts than possible from the ground. However, a ground-based LST will face challenges arising from observational effects such as atmospheric fluctuations and possible biases in photometrically determined redshifts of large samples of galaxies. For measuring baryon acoustic oscillations, JDEM will be capable of surveying the full sky, providing a large statistical advantage over ground-based experiments. Thus, scientifically, JDEM is at present a lower-risk project than ground-based dark energy projects. It has a lower uncertainty in its projected sensitivity. It has superior capabilities for controlling systematic uncertainties for all primary techniques except baryon acoustic oscillations, for which it may have statistical advantages. Finally, it has the important capability of making measurements at higher redshift, which could be critical for probing small effects.

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[57] A. Albrecht, G. Bernstein, R. Cahn, W.L. Freedman, J. Hewitt, W. Hu, J. Huth, M. Kamionkowski, E.W. Kolb, L. Knox, J.C. Mather, S. Staggs, and N.B. Suntzeff, 2006, *Report of the Dark Energy Task Force*, available at http://arxiv.org/ftp/astro-ph/papers/0609/0609591.pdf, Section IX, pp. 53-78.

In practice, JDEM and ground-based projects are likely to be complementary. Systematic uncertainties will limit the ultimate level of sensitivity of both. The four primary observational techniques for exploring dark energy are sensitive in different and complementary ways to dark energy and other cosmological properties, and, although JDEM will implement a combination of at least two techniques, JDEM and a ground-based project together could implement a larger combination. Furthermore, the systematic challenges to space-based and ground-based projects are somewhat different. Together, JDEM and ground-based projects are likely to yield important consistency checks and possibly improved sensitivity over that with JDEM alone.

Science Readiness and Risk

JDEM faces risks arising from systematic uncertainties and from competition. The principal science risk to JDEM arises from the challenge to control systematic uncertainties to the sub-percent level required to achieve at least the factor-of-10 improvement in sensitivity called for by the Dark Energy Task Force. None of the observational techniques that may be employed by JDEM has yet demonstrated the ability to reach this level of control. Nonetheless, the expectation is that each technique can be calibrated to sufficient accuracy using existing theoretical and observational strategies. Considerable progress has been made in understanding sources of systematic uncertainty and in developing strategies to mitigate systematic effects. Factors that limit the ultimate JDEM sensitivity will be addressed by intermediate-term observational and theoretical projects, as well as by control data collected by JDEM itself and by other observations. Moreover, JDEM will benefit from two or more complementary observational techniques with differing systematic limitations. Whereas the Dark Energy Task Force projects that a JDEM mission combining at least two techniques will produce at least a factor-of-10 improvement in sensitivity over present projects, it also projects an improvement of at least a factor of 8 under worst-case assumptions regarding the ability of JDEM to control systematic errors. Such a worst-case improvement factor will still represent a critical improvement in our understanding of the nature of dark energy.

As discussed in the previous subsection, JDEM will face competition from ground-based dark energy experiments. Multiple ground-based experiments using a variety of techniques are being planned, some for the period preceding a JDEM launch and more aggressive experiments for the future. These experiments will significantly advance the sensitivity of dark energy measurements if they control their systematic uncertainties much better than has been possible to date on the ground. The unique scientific impact of JDEM could be reduced by these other experiments if they achieve their targeted sensitivities and if astrophysical systematic uncertainties prevent JDEM from achieving its sensitivity goals, although such an outcome seems unlikely. JDEM, by virtue of being based in space, will generally have better control of observational systematic uncertainties. It will also collect large samples of control data, and it will benefit from progress in understanding sources of systematic uncertainty as observational techniques and associated astrophysics theory advance. In practice, the implementation of a variety of measurement techniques, in space and on the ground, will provide a considerable degree of complementarity, which will improve overall sensitivity to dark energy and will provide important cross-checks of results.

Steps for Moving Forward

In order to prepare for implementation of one of the JDEM concepts, further progress should be made in understanding sources of systematic uncertainty and in developing strategies to mitigate systematic effects. All techniques for measuring effects of dark energy will benefit greatly from both observational and theoretical studies. For supernovas, issues include whether evolutionary effects are important, whether Type Ia supernova explosions are isotropic, and whether the light curve is standard. All of these effects can be empirically calibrated, but the issue is whether they can be calibrated to required sub-percent level accuracy. Both detailed observations and theoretical modeling performed over the next few years will help substantially to reduce the uncertainties. Weak-lensing studies rely on extremely accurate measurements of the image profile and shape obtained from the telescopes over a large field and large time baseline. Weak-lensing results from ground-based facilities are not at the required level for the control of systematic errors, but space telescopes offer a significant improvement. Comparison of shear models, both from simulations and from ground-based observations using a variety of weak-lensing techniques, would improve understanding of the reliability of profile and shape measurements. For baryon acoustic oscillations, a concern is whether nonlinearities from gravitational effects bias the signal of the acoustic scale. Large redshift surveys from ground-based studies can provide knowledge of the systematic errors down to the percent level but will not explore sub-percent levels. However, theoretical models involving both analytic and numerical analysis will be very useful for understanding the systematic errors at the sub-percent level. The Dark Energy Task Force recommended high priority for near-term funding of projects that will improve the understanding of, or reduce, dominant systematic effects in dark energy measurements. With adequate support, substantial progress in theoretical and observational studies designed to calibrate the different distance estimators will be made within a few years.

Any one of the three proposed JDEM concepts that the committee evaluated would strongly advance the understanding of dark energy. Nonetheless, as both observational techniques and theory rapidly advance, a different combination of observational techniques may be found to achieve better sensitivity. Ongoing analysis will be important for determining which combination of techniques can best achieve the Beyond Einstein goal.

Science Assessment Summary

Understanding the nature of dark energy is one of the most important scientific endeavors of the present era. JDEM will significantly advance both this endeavor and a broad array of other astrophysical studies. 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 measurement that discovers that the expansion history is not consistent with a cosmological constant will have a fundamental and revolutionary impact on physics and astronomy.

While there are several current and planned dark energy experiments, JDEM will significantly improve sensitivity to the effects of dark energy. The principal science risk to JDEM arises from the challenge to control systematic uncertainties to the level required for significant improvement. Techniques for the control of observational systematic uncertainties to required levels have not yet been demonstrated, and astrophysical systematic uncertainties for some measurement techniques may be irreducible. If JDEM is not able to control systematic uncertainties adequately, its improvement in dark energy sensitivity may be more modest than projected. JDEM will mitigate these risks by employing multiple complementary observational techniques and by collecting rich data sets to improve the control of systematic uncertainties and to provide valuable cross-checks. Many of JDEM's advantages stem from the fact that it is space-based. Thus, JDEM could improve sensitivity to the effects of dark energy by an order of magnitude with respect to present measurements, and it is likely to improve significantly on new, ground-based experiments despite the challenges of controlling systematic uncertainties. In fact, the clarity provided by JDEM's precision measurements is likely to be needed to confirm other dark energy measurements.

Wide-field optical and NIR surveys required for dark energy studies will offer large, rich data sets for a broad array of other astrophysics studies, providing tremendous discovery potential. A full-sky, NIR spectroscopic survey such as ADEPT proposes for studying baryon acoustic oscillations, 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 era when galaxies grow, along with data for many other astrophysics studies (Table 2.20). A low-background, wide-field imaging survey, such as DESTINY and SNAP propose for studying weak lensing, would provide a much larger diffraction-limited NIR survey than is otherwise available. This survey would revolutionize understanding of how and when galaxies acquire their mass, as well as providing data for many other astrophysics studies.

LASER INTERFEROMETER SPACE ANTENNA

Introduction

According to Einstein's general theory of relativity, mass in accelerated motion may lead to the emission of gravitational radiation. Like electromagnetic radiation (light, x-rays, and so on), gravitational waves travel at the speed of light, have two modes of polarization, and cause effects transverse to the direction of propagation.

TABLE 2.20 Joint Dark Energy Mission (JDEM): Summary of Scientific Evaluation

	Potential Contributions to Science	
	Beyond Einstein	Broader Science
Factors		
Revolutionary discovery potential	A measurement that discovers that the expansion history of the universe is not consistent with a cosmological constant will have a fundamental and revolutionary impact on physics and astronomy.	Wide-field optical and near-infrared (IR) surveys will offer tremendous discovery potential. A spectroscopic survey would open the emission-line universe, and an imaging survey would produce the richest data set ever for studies of galaxy evolution.
Science readiness and risk	Systematic uncertainties may limit JDEM to modest improvements over ground-based studies.	Because of the exquisite data sets that JDEM surveys will produce, there is little risk to the broader science impact.
Mission Uniqueness		
Versus other space missions	A comparable European space mission concept is under discussion but is not yet approved.	There are no comparable spectroscopic or imaging surveys to the proposed JDEMs.
Versus ground-based instruments	JDEM affords better control of systematic uncertainties than ground-based experiments for supernova and weak-lensing studies, and better statistics for baryon acoustic oscillations.	Wide-field cameras based on the ground cannot access the near-IR and have much poorer resolution at optical wavelengths due to atmospheric effects.

NOTE: See Appendix G in this report for definitions of acronyms.

But unlike electromagnetic radiation, which consists of varying electromagnetic fields in spacetime, gravitational radiation is the result of ripples in the fabric of spacetime itself. Electromagnetic radiation is strongly scattered or absorbed by dense regions of matter, and thus the radiation that we see, say from a supernova or a gamma-ray burst, often comes from secondary processes in the expanding shell of gas. By contrast, gravitational waves are extremely weakly absorbed, and thus they propagate directly to us from the region of accelerated bulk motions of massive objects. Gravitational waves are a uniquely powerful means of peering into those regions of the universe where the spacetime curvature is greatest and most rapidly changing and of seeing to the most distant reaches of the universe in space and time. Gravitational waves open a unique window onto the cosmos that will provide insights that cannot be gained from electromagnetic or cosmic-ray probes.

There is compelling evidence from observations of the decaying orbits of binary pulsars that gravitational waves exist. For example, in the binary pulsar B1913+16, the rate of decrease of the orbital period agrees to better than half a percent with the prediction of general relativity of the loss of orbital energy through the emission of gravitational waves.[58] The discovery of this system and the confirmation of Einstein's theory were recognized with the 1993 Nobel Prize to Joseph Taylor and Russell Hulse. Data from other binary pulsars confirm these conclusions.

Nevertheless, despite considerable effort to build and operate gravitational-wave detectors on the ground, gravitational waves have not been detected directly to date, because the astrophysical signals are exceedingly weak in the frequency regime accessible to the ground-based experiments, currently operating at their design sensitivities. Space-based instruments, which are not subject to Earth's seismic noise, can "hear" low-frequency gravity

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[58] J.M. Weisberg and J.H. Taylor, 2005, The relativistic binary pulsar B1913+16: Thirty years of observations and analysis, pp. 25-32 in *Binary Radio Pulsars* (F.A. Rasio and I.H. Stairs, eds.), ASP Conference Series 328, Astronomical Society of the Pacific, San Francisco, Calif.

TABLE 2.21 Laser Interferometer Space Antenna (LISA): Mission Description

Parameter	Value
Primary measurement	Gravitational waves
Observatory type	Three satellites in triangular formation; intersatellite distance variations measured by laser interferometry
Projected years in orbit	5 yr after beginning of science operation
Type of orbit	Heliocentric at 1 AU, 20° behind Earth
Mission phases	Single full-time data-collecting phase after commissioning
Science operations	Observation of total sky all the time; no pointing or scheduling needed or possible
Other mission characteristics	Drag-free proof masses

TABLE 2.22 Laser Interferometer Space Antenna (LISA): Mission Instrument Properties

Instrument	Spectral Range	Spatial Resolution	Spectral Resolution	Collecting Area	Field of View
Gravitational wave antenna	3×10^{-5} Hz to 0.1 Hz	1° angular resolution for MBH mergers	Measures waveform directly to fractions of a cycle over hundreds to thousands of cycles	10^{13} sq. km	All sky, all the time

waves produced by a rich variety of known and exotic sources. The direct detection of gravitational waves will revolutionize our ability to observe the universe.

The Laser Interferometer Space Antenna is a proposed gravitational-wave antenna in space whose goal is to detect gravitational waves, study their properties, and use them to create a radically new form of astronomy. A rich variety of strong low-frequency gravity wave signals is expected, and these can only be detected from space. LISA will consist of an array of three satellites orbiting the Sun, each satellite separated from its neighbor by about 5 million kilometers. The satellites will fly in an equilateral triangular formation in an Earth-like orbit, but trailing Earth by about 20°. The orbits are chosen to keep the spacecraft close to the vertices of an equilateral triangle throughout the mission. Launch of the three spacecraft will be on a single Atlas V rocket.

A passing gravitational wave will cause minute changes in the relative distance between a fiducial or reference mass (called a proof mass) housed in one of the satellites and identical masses housed in each of the other satellites. Each proof mass is a 2 kg cube made of a gold-platinum alloy. These distance changes are to be measured using laser beams provided by 1 watt diode-pumped 1,064 nanometer Nd:Yag frequency-stabilized lasers coupled to 40-cm-aperture modified Cassegrain telescopes. Each satellite will house two such systems, with each beam directed at one of the two companion satellites. The six beams will be sent between the three satellites (one in each direction), with phases precisely referenced to the reflective surfaces of the proof mass associated with each laser, using an onboard phase measurement system (PMS).

In order that the proof masses respond only to the spacetime strain induced by a gravitational wave, they will be maintained in purely gravitational orbits, protected from nongravitational disturbance forces such as solar radiation pressure, using a system of drag compensation. Electrostatic sensors will determine the location of each proof mass within its chamber and send signals to low-force thrusters (called micronewton thrusters), which will nudge the spacecraft to keep the proof masses at the centers of their respective chambers. This disturbance reduction system (DRS) is a critical aspect of LISA technology, which will be tested on the LISA Pathfinder mission (see in Chapter 3 the section "LISA Mission"). Employing phase-sensitive detection techniques, LISA will use the phases of each of the six laser beams to monitor the distance between the three pairs of proof masses (the relative location of the pair of proof masses within each satellite is monitored using internal laser optics). The changes in physical distance along each arm of the triangle induced by a gravitational wave will be reflected in phase changes in each of the six beams. Certain combinations of these six phase signals are directly related to the gravitational-wave amplitude, while another combination is insensitive to the waves but contains information about instrumental noise sources. The basic mission characteristics and instrument properties are summarized in Tables 2.21 and 2.22.

LISA will be sensitive to gravitational waves in the low-frequency band, between 3×10^{-5} and 0.1 Hz, with sensitivity to proof-mass displacements at the level of tens of picometers, corresponding to a fractional displacement sensitivity of 10^{-20}. It is worth pointing out that the raw displacement sensitivity required for LISA is a million times *less* stringent than that already achieved by the ground-based laser interferometers, LIGO in the United States, and Virgo and GEO600 in Europe, although the ground-based instruments operate at higher frequencies.[59] But because of the long arms, the fractional sensitivity, or strain sensitivity, is so high that many of the target sources for LISA will be rather easy to detect, in the sense that their expected signal amplitudes will be between 10 and 10,000 times higher than the instrumental noise. Indeed, there are guaranteed detections: many known nearby binary star systems whose gravitational-wave signals are precisely calculable and are sufficiently strong that they will be used as verification and calibration sources.[60]

A gravitational-wave antenna of this sensitivity will open up a completely new window on many of the most interesting objects in the universe. During its proposed 5-year mission, LISA may be expected to detect gravitational waves from the inspiral and merger of massive black holes in the centers of galaxies or stellar clusters at cosmological distances, and from the inspiral of stellar-mass compact objects 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 verify if the black holes of nature are truly described by the predicted geometry of Einstein's theory of general relativity. 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. These measurements will enable the construction of 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, and it may study whether there are more than the two polarizations predicted by general relativity.

Mission Science Goals

Contribution to Beyond Einstein Science

LISA will contribute directly to Beyond Einstein goals by studying the properties of cosmic black holes, testing general relativity in new regimes, and making interesting cosmological measurements (see Table 2.23).

There is strong and growing observational evidence for the existence of massive astrophysical black holes. The most convincing case comes from our own Galaxy, where a population of stars is seen orbiting a compact object of 3.7 million solar masses,[61] but evidence supports the conclusion that black holes with masses between 10^5 and 10^9 solar masses reside in the centers of nearly all nearby massive galaxies. There is also a robust correlation between the mass of the central black hole and both the luminosity and velocity dispersion of the host galaxy's central bulge.[62] How such massive holes formed and what the origin of this correlation is are still mysteries. The leading scenario involves the repeated mergers of, and gas accretion by, galactic-center black holes following the merger of their respective host galaxies. However, it is not known whether the original "seed" black holes were 30 to 300 solar mass holes formed from the collapse of heavy-element-free Population III stars in the early universe (redshift ~20), or 10^5 solar mass holes formed much later from the collapse of material in protogalactic disks.

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[59] F.J. Raab, representing the LIGO Scientific Collaboration and other laser interferometer groups, 2006, The status of laser interferometer gravitational-wave detectors, *J. Phys. Conf. Ser.* 39:25-31.

[60] K. Danzmann, 1997, LISA—an ESA cornerstone mission for a gravitational-wave observatory, *Class. Quantum Grav.* 14:1399-1404.

[61] R. Schödel, T. Ott, R. Genzel, A. Eckart, N. Mouawad, and T. Alexander, 2003, Stellar dynamics in the central arcsecond of our galaxy, *Astrophys. J.* 596:1015-1034; A.M. Ghez, S. Salim, S.D. Hornstein, A. Tanner, J.R. Lu, M. Morris, E.E. Becklin, and G. Duchene, 2005, Stellar orbits around the galactic center black hole, *Astrophys. J.* 620:744-757.

[62] J. Kormendy and D. Richstone, 1995, Inward bound: The search for supermassive black holes in galaxy nuclei. *Ann. Rev. Astron. Astrophys.* 33:581-628; K. Gebhardt, R. Bender, G. Bower, A. Dressler, S.M. Faber, A.V. Filippenko, R. Green, C. Grillmair, L.C. Ho, J. Kormendy, T.R. Lauer, J. Magorrian, J. Pinkney, and D. Richstone, 2002, The slope of the black-hole mass versus velocity dispersion correlation, *Astrophys. J.* 574:740-753.

TABLE 2.23 Laser Interferometer Space Antenna (LISA): Beyond Einstein Science Programs

Science	Program	Program Characteristics		Program Significance
Science definition programs	Formation of massive black holes	Science question	How and when do massive black holes form?	Observations will detect massive black hole binary mergers to z = 15 and shed light on when massive black holes formed.
		Measurements	Gravitational waveform shape as a function of time from massive black hole binary inspiral and merger	
		Quantities determined	Mass and spin of black holes as a function of distance	
	Test general relativity in the strong-field regime	Science question	Does general relativity correctly describe gravity under extreme conditions?	Measurement of the detailed gravitational waveform will test whether general relativity accurately describes gravity under the most extreme conditions.
		Measurements	Gravitational waveform shape as a function of time from massive black hole binary inspiral and merger	
		Quantities determined	Evolution of dynamical spacetime geometry, mass and spin of initial and final holes	
	History of galaxy and black hole co-evolution	Science question	How is black hole growth related to galaxy evolution?	Observations will trace the evolution of massive black hole masses as a function of distance or time, and will shed light on how black hole growth and galactic evolution may be linked.
		Measurements	Gravitational waveform shape as a function of time from massive black hole binary inspiral and merger	
		Quantities determined	Mass as a function of distance	
Additional Beyond Einstein science	Map black hole spacetimes	Science question	Are black holes correctly described by general relativity?	Observations will yield maps of the spacetime geometry surrounding massive black holes and will test whether they are described by the Kerr geometry predicted by general relativity. They will also measure the parameters (mass, spin, shape) of the holes, and test whether they obey the no-hair theorems of GR.
		Measurements	Gravitational waveform shape from small bodies spiraling into massive black holes (EMRI)	
		Quantities determined	Mass, spin, multipole moments, spacetime geometry close to hole	
	Cosmological backgrounds	Science question	Are there gravitational waves from the early universe?	First-order phase transitions or cosmic strings in the early universe could leave a background of detectable waves.
		Measurements	Stochastic background of gravitational waves	
		Quantities determined	Effective energy density of waves vs. frequency	
	Cosmography, dark energy	Science question	What is the distance scale of the universe?	If redshift of source or host galaxy can be determined, then precise, calibration-free measurements of the Hubble parameter and other cosmological parameters could be done, significantly constraining dark energy.
		Measurements	Gravitational waveform shape and amplitude measurements yield luminosity distance of sources directly	
		Quantities determined	Luminosity distance	

NOTE: See Appendix G in this report for definitions of acronyms.

Furthermore, it has proven difficult to find a process whereby the holes in the merged galaxy can efficiently find each other and merge on a fast-enough time scale. By studying massive black hole mergers beyond redshift 10 for holes between 10^5 and 10^7 solar masses and to redshift 10 to 20 for holes between 100 and 10^5 solar masses, LISA will be able to search for the earliest seed black holes.

In addition, by matching the observed gravitational waveform to a bank of theoretically predicted template waveforms, a technique that has been developed for use in the ground-based interferometers, LISA will be able to make very precise measurements of black hole masses and distances. Furthermore, in the hierarchical merger scenarios, the rate of detectable mergers may be as high as two per week. Thus, LISA will be able to trace the history of the growth of black hole masses and thereby shed direct light on how their formation and growth may be linked to the evolution of galaxies.

Because the final inspiral and merger of the two massive holes is dominated by the mutual gravity of the holes, which consist themselves of pure warped spacetime geometry, the orbit and gravitational-wave signal will reflect strong-field, dynamical, curved-spacetime general relativity in its full glory. Detailed comparisons between the measured waveforms and theoretical waveforms calculated from combinations of analytical and numerical solutions of Einstein's equations (a method called matched filtering) will give a rich variety of tests of the theory in a regime that has hitherto been inaccessible to experiment or observation. For example, there is now evidence from numerical solutions of Einstein's equations that the spin of the individual black holes may play a critical role in how they merge; depending on the magnitude and alignment of the spins, the mergers could be very rapid or could experience a momentary "hang-up," with significant consequences for the observed waveform.[63] These are the consequences of "frame dragging," a fundamental prediction of Einstein's theory that has been probed in the solar system using Gravity Probe B, Laser Geodynamics Satellites (LAGEOS), and lunar laser ranging; frame dragging has been hinted at in observations of accretion onto neutron stars and black holes. Observing the effects of frame dragging in such an extreme environment would be a stunning test of general relativity. Furthermore, with spinning progenitors, the final black hole could experience a substantial recoil resulting from the emission of linear momentum in the gravitational waves, large enough to eject it completely from the host galaxy.

Matched filtering of the inspiral and merger waveforms will also provide measurements, some with very high precision, of such quantities as the masses and spins of the initial and final black holes, the distance to the system, and its location on the sky. For example, for two 10^6 solar mass nonspinning black holes merging at $z = 10$, the total mass of the system could be measured to 0.1 percent and the luminosity distance could be measured to 30 percent; at $z = 1$, the corresponding figures are 0.001 percent and 2 percent, respectively.[64]

In addition, LISA will be able to detect "ringdown" waves, which are waves emitted by the distorted final black hole as it settles down to a stationary state. These waves have discrete frequencies and damping rates that depend on the mass and spin of the hole. By carrying out "black hole" spectroscopy on this discrete spectrum of ringdown waves, LISA will be able to test whether the geometry obeys the "no-hair" theorem of the Kerr metric predicted by general relativity. If the basic ideas of massive black hole growth are qualitatively correct, LISA may expect to see tens to hundreds of events per year for inspirals at the high-mass end. For inspirals at the low-mass end, the rates are highly uncertain.

Another class of sources, called extreme mass-ratio inspirals (EMRI), may provide additional quantitative tests of the spacetime geometry of black holes. These involve a stellar-mass compact object spiraling into a massive (10^6 solar mass) black hole. Over the 10^4-10^5 eccentric, precessing orbits traced out by the smaller mass, the emitted waves encode details about the spacetime structure of the larger hole with a variety of distinct signatures. In addition to providing determinations of the black hole's mass and angular momentum to fractions of a percent, the observations can also be used to test whether the spacetime that encodes the waves is the unique Kerr geometry that general relativity predicts for rotating black holes.[65]

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[63] M. Campanelli, C.O. Lousto, and Y. Zlochower, 2006, Spinning black-hole binaries: The orbital hang-up, *Phys. Rev. D* 74:041501.

[64] E. Berti, A. Buonanno, and C.M. Will, 2005, Estimating spinning binary parameters and testing alternative theories of gravity with LISA, *Phys. Rev. D* 71:084025.

[65] S.A. Hughes, 2006, (Sort of) testing relativity with extreme mass ratio inspirals, pp. 233-240 in *Laser Interferometer Space Antenna: 6th International LISA Symposium* (S.M. Merkowitz and J.C. Livas, eds.), AIP Conference Proceedings, Volume 873, American Institute of Physics, College Park, Md.

TABLE 2.24 Laser Interferometer Space Antenna (LISA): Broader Science Examples

Program	Program Characteristics		Program Significance
Galactic compact binaries	Science question	What is the distribution of binary systems of white dwarfs and neutron stars in our Galaxy?	Could provide a census of compact binary systems not achievable by electromagnetic means, and could survey the systems that are progenitors of high-frequency gravitational-wave sources detectable by ground-based interferometers. Population statistics could improve models of binary stellar evolution.
	Measurements	Sinusoidal gravitational waveforms	
	Quantities determined	Orbital frequencies, sky distribution	

LISA will also be able to test the nature of the gravitational waves and test specific alternative theories to general relativity. Using massive-black-hole inspiral data, LISA will be able to measure any hypothetical difference in the speeds of gravitational waves and of light with a precision of parts in 10^{17} and test whether or not the "graviton," the putative quantum particle of gravity, has a mass.[66] Because the LISA spacecraft orbit the Sun, they will be sensitive to different mixtures of the polarization modes in the waves from a sufficiently longlasting source and may be able to test whether the general relativistic prediction of only two transverse quadrupolar modes is correct. These would constitute tests of Einstein's theory in an entirely new regime.

Because binary black hole inspirals are controlled by a relatively small number of parameters, such as mass, spin, and orbital eccentricity, they are good candidates for standard candles.[67] They are good candidates because the frequency and frequency evolution of the waves are determined only by the system's parameters, while the wave amplitude depends on those same parameters and on the luminosity distance to the source. No complex calibrations are needed. Matched filtering analyses have shown that, for nearly circular inspirals, LISA could measure luminosity distances to a few percent at redshift 2 and to tens of percent at $z = 10$. At the same time, because of the changing orientation of the LISA array with respect to the source, it can also determine the orientation, with precision of better than a degree for massive inspirals at $z = 1$. If this angular and distance resolution were enough to link a LISA event with a corresponding electromagnetic event in a host galaxy or quasar and thereby to yield a redshift, LISA would contribute a direct, absolute calibration of the cosmic distance scale (Hubble diagram) that relies only on fundamental physics rather than on the complex chain of largely empirical distance ladders on which researchers rely at present. A 2 percent measurement of distance combined with a redshift at $z = 1$ would give a 2 percent measurement of the dark energy parameter w. The combination of several such measurements could give a dark energy bound that begins to be competitive with JDEM. The main challenge will be in using LISA's angular resolution to identify the host galaxy.

Contributions to Other Science

Because of the apparent close connection between galactic center black holes and the structure of their host galaxies, information on the formation and growth of massive black holes over cosmic time will feed into models of galactic formation and evolution. The study of EMRIs using coordinated gravitational-wave and electromagnetic observations will improve the understanding of the stars and gas in the close vicinity of galactic black holes. Within our own Galaxy, LISA will measure the orbits and determine the locations of up to 10,000 close binary systems consisting mainly of white dwarfs; as such systems are the precursors of Type Ia supernovas and millisecond pulsars, such a census will aid in understanding the evolution of such systems (see Table 2.24 for a summary).

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[66] C.M. Will, 1998, Bounding the mass of the graviton using gravitational-wave observations of inspiralling compact binaries, *Phys. Rev. D* 57:2061-2068.

[67] B.F. Schutz, 1986, Determining the Hubble constant from gravitational wave observations, *Nature* 323:310-311.

Opportunity for Unexpected Discoveries

Despite numerous expectations and predictions based on the current knowledge of the universe derived from electromagnetic observations, in fact, the direct knowledge of the gravitational-wave sky is precisely *zero*. The history of astronomy tells us that every new window on the universe has completely transformed the understanding of the cosmos. Such transformations took place when the first telescopes were invented, when radio astronomy began, and when x-ray astronomy started, to name just a few examples. It would be unreasonable to imagine that there will be no surprises when we open the gravitational-wave window.

LISA may well observe signals from new sources that cannot be detected with electromagnetic radiation. Because gravitational waves may originate at very high redshift and propagate without absorption or scattering, LISA could provide the first information of any kind about some types of nonlinear motions of matter and energy. For example, first-order phase transitions of new forces or extra dimensions in the early universe could produce a detectable background of gravitational waves. Such events would occur between an attosecond (10^{-18} seconds) and a nanosecond after the big bang, a period not directly accessible by any other technique. Other potential exotic sources include intersecting cosmic string loops or vibrations and collapses of "boson stars," stars made of hypothetical scalar-type matter.

Assessment of Scientific Impact

LISA will open a revolutionary new window on the universe, using the rippling of spacetime itself rather than fields propagating through spacetime as its source of information about the activities of the sources. It will observe many phenomena that cannot be detected directly by electromagnetic means, such as the inspiral and merger of black holes. LISA will uncover how massive black holes formed and interacted, and it will yield for the first time precise measurements of their masses and spins. It will test how well general relativity accounts for extreme gravity, will verify the dragging of inertial frames in extreme situations, and will check whether black holes are indeed those described by general relativity, tests that cannot be done by any other means or that are prone to uncertainties owing to complex nongravitational physics phenomena. LISA will study how the earliest galactic structures formed in the early universe and will shed light on the merger history of galaxies. It will provide a census of compact binary systems in the Galaxy far beyond what can be done with electromagnetic techniques, and it will measure luminosity distances to high-redshift sources precisely and without complex calibrations. It will also make fundamental measurements of the properties of the gravitational waves themselves. Finally, it may detect waves from processes in the early universe or from exotic or unexpected sources.

No other technique addresses some of the questions that LISA addresses, especially related to the gravitational dynamics of black holes, where *only* gravitational signals can escape the surrounding gas and dust unimpeded. It will also be studying directly the bulk, coherent motions of large masses, which dominantly produce gravitational waves. This production method contrasts with electromagnetic waves, which usually originate in the incoherent superposition of motions of charged particles.

LISA may also provide the first direct detection of gravitational waves, a quest that began in the 1960s. Although the ground-based laser interferometers in the United States and Europe are operating on schedule and at their design sensitivities, they must successfully carry out a sequence of planned upgrades before they reach the level of sensitivity at which they can confidently be expected to see gravitational waves. There is no guarantee that this level will be achieved before the proposed launch and operation of LISA. At the same time, there is no direct competition from the ground-based interferometers even if they should detect waves first. The two approaches are complementary. The ground-based systems are sensitive to the high-frequency gravitational-wave band, between 10 and 1,000 Hz. Their target sources are stellar-mass black hole and neutron star inspirals and mergers, spinning pulsars, neutron star vibrations, and supernova core collapse in the relatively nearby universe. They do not address the same science that LISA does. However, there are some synergies between the two approaches: for example, some of the close compact binary systems that LISA is expected to detect in the millihertz band are the precursors to the kilohertz inspiral sources detectable by the ground-based interferometers.

Science Readiness and Risk

LISA's quest to detect gravitational waves is based on our understanding of general relativity (indeed of any theory of gravity that is compatible with special relativity), where the emission of gravitational waves is required by the existence of a fundamental limiting speed for the propagation of information. But because the most interesting sources involve extreme gravity and relativistic speeds, it is important to ask whether techniques for solving Einstein's equations are sufficiently advanced to predict confidently the gravitational waves from the sources of interest and to interpret the data taken. Secondly, the mission is based on our understanding of sources that might actually exist, so we must ask whether the astrophysics is sufficiently well understood to predict with reasonable confidence that LISA will detect interesting sources during its proposed 5-year mission lifetime.

During the past decade, a combination of analytical and numerical work has provided sufficient machinery to yield robust predictions from general relativity for the gravitational-wave signal from massive-black-hole coalescences, including the inspiral, merger, and ringdown phases. Indeed, recent breakthroughs in "numerical relativity" have been critical in providing solutions that link the inspiral signal, which is determined using analytical approximation techniques (commonly known as post-Newtonian theory), with the ringdown signal, which is determined from perturbation theory of black holes.[68] These new methods are now being applied to the more complex and interesting case of mergers of rapidly spinning black holes, and substantial progress is likely during the next few years, well in advance of LISA.

The EMRI problem is somewhat different: there the small compact object can be viewed as a perturbation of the background spacetime of the large black hole, but one must take into account the "backreaction" of the small body's gravitational field on itself, including the damping of the orbit due to the emission of gravitational waves. Despite considerable progress, substantial work remains to be done to develop waveform predictions for LISA that will cover the hundreds of thousands of expected orbits with sufficient accuracy. For the more conventional sources, such as the galactic close binary systems, textbook general relativity is completely adequate.

Because of LISA's high sensitivity, it is expected that many sources will have their signals superimposed simultaneously on the data stream. Recently, a program of LISA "mock data challenges" has shown substantial promise in demonstrating the ability to extract multiple signals, ranging from inspiral "chirps" to steady sinusoidal signals from simulated data streams.[69]

On the astrophysics side, there are a number of assured sources, including well-documented, close binary systems in our Galaxy, which will be used as verification or calibration signals during the first year of science operation. A foreground of waves from galactic and extragalactic close white-dwarf binaries is expected to be detectable; in fact, in some frequency ranges this foreground will represent an unresolvable gravitational-wave noise stronger than the instrumental noise. Predicted event rates for massive-black-hole inspirals are uncertain by a factor of 10 but indicate that LISA is likely to detect them even in 1 year of operation. For EMRIs, the rates are even more uncertain; this could be a risk factor if the mission fails to achieve its 5-year lifetime.

Steps for Moving Forward

Because LISA is a joint NASA-ESA project, the committee considered how to maintain a level of synchronicity between the schedules of the two agencies. In late 2009, ESA plans to select two candidate missions for an "L-1" class launch around 2018 from proposals submitted in response to its Cosmic Visions 2025 opportunity. As LISA is likely to be the most developed project among the possible contenders, it will be in a strong position for selection to enter ESA's Definition Phase (roughly equivalent to NASA's Phase B). The final selection of a single mission to enter the implementation phase is expected to occur in late 2012 and will include the Pathfinder results

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[68] F. Pretorius, 2005, Evolution of binary black hole spacetimes, *Phys. Rev. Lett.* 95:121101; J.G. Baker, J. Centrella, D. Choi, M. Koppitz, and J. van Meter, 2006, Gravitational wave extraction from an inspiralling configuration of merging black holes, *Phys. Rev. Lett.* 96:111102; A. Buonanno, G.B. Cook, and F. Pretorius, 2007, Inspiral, merger, and ringdown of equal-mass black-hole binaries, *Phys. Rev. D* 75:124018.

[69] K.A. Arnaud et al., 2006, The mock LISA data challenges: An overview, pp. 619-624 in *Laser Interferometer Space Antenna: 6th International LISA Symposium* (S.M. Merkowitz and J.C. Livas, eds.), AIP Conference Proceedings, Volume 873, American Institute of Physics, College Park, Md.

TABLE 2.25 Laser Interferometer Space Antenna (LISA): Summary of Scientific Evaluation

	Potential Contributions to Science	
	Beyond Einstein	Broader Science
Factors		
Revolutionary discovery potential	LISA will open a unique new window on the universe, will test general relativity in the most extreme regimes, will study the formation and evolution of massive black holes, and will measure absolute distances on cosmological scales. Detection of gravitational waves is assured.	LISA could detect waves from exotic or unexpected sources, such as cosmic strings or early universe phase transitions.
Science readiness and risk	Understanding of the underlying theory and data analysis is robust. The main risk is the uncertainty in rates of mergers involving massive black holes.	Low risk: detection of many galactic binaries is assured.
Mission Uniqueness	No similar or competing missions are envisioned.	No similar or competing missions are envisioned.

in the evaluation process. Aggressive technology development will be needed to advance the technical readiness of the mission so that LISA will be ready to enter a NASA implementation phase in line with ESA's schedule.

Science Assessment Summary

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 (see Table 2.25). During its proposed 5-year mission, LISA is expected to detect gravitational waves from the inspiral and merger of massive black holes in the centers of galaxies or stellar clusters at cosmological distances, and from the inspiral of stellar mass compact objects into massive black holes. The study of these waves can trace the growth of massive holes and the formation of galactic structure, test general relativity in the hitherto untested strong-field dynamical regime, and test whether the black holes found in nature are truly described by Einstein's theory. LISA can measure absolute distances to systems on the far side of the universe and could contribute to cosmological measurements, such as of dark energy. LISA will measure both the speed and the polarization states of gravitational waves. LISA could also detect waves from exotic sources such as cosmic strings or phase transitions in the early universe. LISA can measure signals from close binaries of white dwarfs, neutron stars, or stellar-mass black holes in the Milky Way and nearby galaxies. These measurements will enable the construction of a census of compact binary objects throughout the Galaxy.

SCIENCE SUMMARY

This section summarizes the committee's assessment of the contribution that the candidate missions would make to the Beyond Einstein science questions. The summary captures the strengths, scientific uncertainties, readiness, and uniqueness of the associated scientific programs.

What Powered the Big Bang?

Inflation Probe is the mission that most directly addresses the question, What powered the big bang? IP aims to study the conditions that existed during the time of inflation, when the universe expanded by 30 orders of magnitude, creating nearly all particles and radiation. The inflationary period cannot be observed directly. However, inflation does leave distinct imprints that can be observed to determine its properties. The IP mission concepts take one of two approaches. The first approach studies the imprint of gravitational waves on the cosmic microwave background. This measurement will probe the energy scale of inflation, possibly around 10^{16} GeV, far beyond the capabilities of ground-based accelerators. The second approach measures inflation's effect on primordial density fluctuations by observing the amount of structure in the universe on various length scales. It is also possible that LISA will observe the early universe during inflation directly by detecting a gravitational-wave background produced during this era; however, most theories predict a signal that is beyond LISA's reach.

There are ongoing and vigorous efforts to develop technology and measurement techniques to achieve the estimated 30 nK sensitivity required for a CMB polarization mission. Control of instrumental and observational systematic effects has yet to be sufficiently understood. In addition, the polarized galactic foreground is an estimated 30 times bigger than the expected signal. It has yet to be proven that it can be removed with high enough precision to reveal an unambiguous primordial signal. These issues are being addressed with ground-based and suborbital missions. However, there is a clear need for more research in these areas. Finally, the theory indicates that the signal may be too small to be detected with the missions as they are currently defined. Advances in technology, observations, and theory are likely to clarify this risk. This makes the selection of a CMB polarization mission premature at this time.

The technique of using structure measurements is less subject to systematic and measurement uncertainties than the polarization measurement. It must be combined with accurate low-redshift surveys and high-quality CMB anisotropy data that either exist or will be mature in the near future. The result will be a strong constraint on inflationary models but not a measurement of the energy scale of inflation. Significant progress measuring the amount of structure in the universe on various length scales has already been made from the ground with Sloan Digital Sky Survey (SDSS). More importantly, ongoing and future ground-based optical measurements of galaxies using Lyman-alpha emission could prove to be as significant as space-based approaches. Finally, no matter how the structure method is carried out, the energy scale of inflation would still need to be measured.

How Do Black Holes Manipulate Space, Time, and Matter?

Gravitational waves and black holes are among the most interesting predictions of Einstein's theory of gravity. LISA will use its high-signal-to-noise detector to test Einstein's theory of general relativity in the strong-field dynamical regime and to map spacetime around a black hole by detailed studies of low-frequency gravitational waveforms. By observing the mergers of pairs of massive black holes, LISA will test whether general relativity accurately describes gravity under the most extreme possible conditions. These will provide fundamentally new measurements of the distortion of spacetime near a black hole. As small bodies spiral into massive black holes, they trace tens of thousands of orbits and emit waves that encode details of the spacetime structure around the massive black hole. By detecting these waves, LISA will provide a rigorous and clean test of whether spacetime is described by the Kerr geometry predicted by general relativity for rotating holes and measure black hole masses and spins to a fraction of a percent.

The main science risk to LISA's ability to test general relativity is the event rates, which may be smaller than predicted. Predicted rates for massive-black-hole inspirals are uncertain by a factor of 10, but they indicate that LISA is likely to detect them even in 1 year of operation. But for small-body inspirals into massive black holes, the rates are even more uncertain: this could be a risk factor if the mission fails to achieve its 5-year lifetime. In terms of scientific readiness, the framework for interpreting LISA waveforms has recently been made more robust.[70] The theory for inspirals has been adequate for quite some time, but recently numerical relativity techniques have advanced to the point that black hole merger waveforms can be predicted with confidence.

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[70] F. Pretorius, 2005, Evolution of binary black hole spacetimes, *Phys. Rev. Lett.* 95:121101; J.G. Baker, J. Centrella, D. Choi, M. Koppitz, and J. van Meter, 2006, Gravitational wave extraction from an inspiralling configuration of merging black holes, *Phys. Rev. Lett.* 96:111102; A. Buonanno, G.B. Cook, and F. Pretorius, 2007, Inspiral, merger, and ringdown of equal-mass black-hole binaries, *Phys. Rev. D* 75:124018.

LISA is unique in that no other facility can probe the low-frequency regime that contains the majority of interesting astrophysical signals. Seismic noise prevents ground-based detectors such as LIGO and VIRGO from accessing this regime.

Constellation-X will also probe the geometry of the region near black holes by observing hot, x-ray emitting material as it spirals into the hole in an accretion disk. The motion of hot blobs in the disk can be observed using time-resolved, high-resolution x-ray spectroscopy, and overall distortions in the shapes of composite lines from the disk can be modeled to determine the spacetime geometry and measure the black hole spin. The science risk lies in understanding the magnetohydrodynamics that may be needed to connect the x-ray observations to the detailed properties of the black hole's spacetime metric. If the orbits of hot blobs are ballistic in the inner regions of the accretion disk, the measurements will be simpler to interpret. Con-X will be able to constrain black hole masses and spins given a Kerr metric, providing important information on black hole formation scenarios. If, however, the observations do find deviations from the expected spacetime geometry it will be difficult to confidently ascribe these to deviations from general relativity because of the uncertainty in the accretion physics. For this reason, the committee found LISA's measurements of spacetime surrounding black holes to be a better precision test of general relativity.

Current x-ray missions have already detected the line shape distortions due to general relativistic effects; however, no proposed x-ray facility other than Con-X has the needed combination of efficiency and resolution to extend this technique to time-resolved measurements.

In addition to understanding how black holes distort spacetime, the Beyond Einstein Program seeks to understand how they are formed and evolve and how they interact with galaxies and clusters. LISA, Con-X, BHFP, and JDEM will all make significant contributions to different aspects of this important problem. Theory tells us that very massive ($M_h > 10^7 M_{sun}$) black holes in the centers of galaxies should become increasingly rare at high redshift; however, there are currently no observational constraints on the black hole mass distribution from above $z \sim 7$. Here LISA promises to be revolutionary, by detecting massive-black-hole binary mergers out to $z \sim 15$-20, measuring the high-redshift mass distribution in the range 10^4-$10^8 M_{sun}$. This will be crucial to revealing how galaxies with black holes formed and merged in the early universe, and how black hole growth and galactic evolution may be linked. The gravitational-wave signals unambiguously yield masses for both the merging black holes and the luminosity distance, which can be converted to redshift given a cosmology. The principal uncertainty in the quality of this measurement is the unknown merger rates. However, even a few detections will be very interesting.

JDEM will also constrain the high-z luminous black hole population by using its near-infrared sensitivity to extend SDSS-like surveys well beyond redshifts of 6.4 (the highest redshift quasar identified by SDSS). Limits on these bright objects (the high-mass end of the black hole spectrum) are particularly constraining to galaxy formation models. X-ray spectral follow-up observations with Con-X SXT's large collecting area will, however, be critical to confidently identifying these objects as black holes and to determining their bolometric accretion luminosity.

At low redshifts ($z < 1$), BHFP will use the penetrating power of high-energy x-rays to locate those accreting massive black holes that are hidden behind large columns of dust and gas over the entire sky and over a relatively wide luminosity (and therefore mass) range, providing another key component of a black hole census. Con-X, with the excellent sensitivity of its hard x-ray telescope, can also detect obscured massive black holes out to $z > 2$ over more limited areas of sky, helping to determine how these objects evolve.

The JDEM, BHFP, and Con-X black hole measurements are all evolutionary in the sense that they extend current optical, infrared, and x-ray surveys to a broader population. However, there is little risk that these measurements will not provide substantial new insights, given the expected data quality. Since they measure accretion luminosity, they are all subject to uncertainties in the conversion of accretion luminosity to hole mass, and this may limit the determination of black hole evolution. However, studies with Con-X and BHFP will likely improve our understanding of accretion physics and therefore the luminosity to mass conversion. These missions are each unique in their ability to uncover specific portions of the black hole content of the universe using wavelength bands only accessible from space.

Finally, BHFP will detect gamma-ray bursts, many of which signal the formation of a stellar mass black hole, out to high redshifts, and through variability measurements can observe stars being shredded as they plunge into black holes. The rate and high-energy x-ray luminosity of these events are uncertain, but detection would be exciting and unique.

What Is the Mysterious Dark Energy Pulling the Universe Apart?

The Joint Dark Energy Mission and Constellation-X will make measurements that characterize the effect of dark energy on the geometry of the universe and/or on the growth of structure. This will yield the ratio of the dark energy pressure to its energy density as a function of time, enabling researchers to distinguish between a cosmological constant, a dynamical evolving field, a modification of general relativity, or some other new physics. The primary purpose of the JDEM missions is to employ at least two of the following three techniques for the exploration of dark energy: (1) using Type Ia supernovas as standard candles to determine the luminosity-distance versus redshift relation; (2) using weak lensing to measure the angular-diameter versus redshift relation, as well as the growth of structure; and (3) using baryon acoustic oscillations to measure angular diameter versus distance. Con-X will use galaxy clusters in two different ways to measure the evolution of dark energy. The first is to determine cluster distances independent of redshift (assuming the gas mass fraction is redshift-independent) and compare these distances to the measured redshift. The second is to measure the effect of dark energy on the growth of structure by determining the mass distribution of clusters as a function of redshift. For the latter measurement, Con-X relies on wide-area cluster surveys from other experiments and will provide the follow-up observations required to accurately determine the cluster masses.

LISA also has the potential to measure the dark energy equation of state, along with the Hubble constant and other cosmological parameters. Through gravitational-waveform measurements, LISA can determine the luminosity distance of sources directly. If any of these sources can be detected and identified as infrared, optical, or x-ray transients and if their redshift can be measured, this would revolutionize cosmography by determining the distance scale of the universe in a precise, calibration-free measurement.

The science risk of the JDEM and Con-X dark energy evolution measurements is the uncertainty in the level of precision and control of the systematic effects. At the present time, weak lensing and baryon acoustic oscillation measurements appear most likely to provide the requisite factor-of-10 improvement over currently available constraints, and each of the proposed JDEM missions employs one of these techniques. The complex astrophysics associated with clusters makes the understanding of systematic effects particularly challenging for this measurement; however, it is possible that detailed x-ray observations of individual clusters with Con-X will improve theoretical understanding sufficiently to allow a precision measurement of w. It is important to use several independent methods of measurement, since they can lead to almost orthogonal constraints and have very different uncertainties. However, because of the importance of controlling systematics, the committee favors the JDEM missions over Con-X for this measurement.

One risk to the success of cosmography with gravitational waves from merging supermassive black holes is the uncertain merger rate. Also at the present time researchers do not know if it will be possible to determine optical counterparts in order to measure redshifts. While the prospect is very exciting, since it would be precise and free of systematic uncertainties, it may not be achievable if, for example, counterparts do not exist. The committee notes that both a wide-FOV near-IR space telescope, such as JDEM, and the Con-X mission would enhance the prospects of counterpart identification if they flew simultaneously with LISA.

All of the JDEM dark energy measurements are being pursued by other experiments. Ground-based telescopes are currently improving statistics of the supernova and baryon oscillation measurements, and future wide-field telescopes will make progress on weak lensing. Space measurements are, however, unique for access to the near-IR, redshift coverage, and stable point spread function, all of which are important for the control of systematics crucial for these measurements. For cluster studies, the eROSITA x-ray mission and ground-based Sunyaev-Zeldovich experiments will significantly improve the dark energy measurements, but it is unlikely that the ultimate precision will be reached without Constellation-X's spectroscopic capability.

Improving measurements of the amount of dark and baryonic matter in the universe is also essential to understanding the amount of dark energy. All of the JDEM mission concepts can contribute to this goal. Wide FOV optical and NIR imaging telescopes can study the large-scale distribution of mass via weak lensing and clarify how galaxies and clusters acquired their mass through both weak lensing and optical photometric surveys. Alternatively, the full-sky NIR spectroscopic survey could revolutionize the understanding of how and when star formation occurred in galaxies.

Constellation-X will make important contributions by detecting and characterizing the warm hot intergalactic medium, believed to contain most of the atoms in the present-day universe. Existing measurements of the baryon content in the early universe from the CMB would allow determination of the present-day distribution of baryonic matter. Con-X also has the potential to probe the nature of dark matter, which constitutes most of the mass of the universe, by observing its effect in galaxy clusters.

The JDEM and Con-X measurements of the matter content and distribution in the universe would be synergistic with the many other efforts in this area being pursued by other ground- and space-based facilities.

Conclusions

As a whole, the suite of five Beyond Einstein missions has tremendous potential to unambiguously answer the three fundamental questions at the core of the program. In its consideration of which mission should fly first, the committee's primary science-evaluation criterion was how directly and unambiguously the different missions would answer one or more of the three questions put forward in NASA's Beyond Einstein roadmap. This evaluation involved balancing breadth, depth, and scientific risk. The committee gave priority to those missions that promise significant advances, even if on a single question, over missions providing more incremental but broader progress touching on many areas, although both sets of contributions were valued. The committee determined that Inflation Probe is the candidate offering the greatest potential for progress in addressing the question, What powered the big bang? JDEM is the mission providing the measurements most likely to determine the nature of dark energy, and LISA provides the most direct and cleanest probe of spacetime near a black hole. Constellation-X, in contrast, provides measurements promising progress on at least two of the three Beyond Einstein questions, but does not provide the most direct, cleanest measurement on any of them. It is, however, an outstanding general astrophysics observatory that will make important advances on other questions set forth in NASA's Beyond Einstein roadmap. The Black Hole Finder Probe will contribute to a black hole census, but it provides less direct measurements of black hole properties than LISA measurements. It was the committee's judgment that for a focused program like Beyond Einstein, it is most important to provide the definitive measurement against at least one of the questions.

With any bold scientific venture there is always risk. For Inflation Probe, the scientific risk is, at the current time, unacceptably high for an investment of the scale of the proposed missions. Uncertain signal levels, foregrounds, and measurement sensitivities suggest that it is premature to proceed with an IP at this time. However, progress from the ground and suborbital platforms will likely be rapid in the next few years, and the maturation of theory and observation in this area will likely make it an exciting future opportunity. JDEM provides the best constraints on the nature of dark energy; however, there is risk that the systematic uncertainties associated with astronomical phenomena will limit the ultimate precision at a level less constraining than what the missions currently estimate, representing less of an advance over ground-based measurements than would be desirable for an investment of this scale. However, it is certainly the case that the ultimate precision and best control of systematics in constraining the DE equation of state will be achieved by space-based observations. Also mitigating the overall scientific risk of the mission is the fact that JDEM is guaranteed to make advances in other areas of Beyond Einstein science, such as the evolution of black holes and matter content of the universe. These two factors, in the committee's view, make a strong case for a JDEM in spite of the risk posed by uncertain systematic effects. On purely scientific grounds, LISA is the mission that is most promising and least scientifically risky. Even with pessimistic assumptions about event rates, it should provide unambiguous and clean tests of the theory of general relativity in the strong-field dynamical regime and be able to make detailed maps of spacetime near black holes. Thus, the committee gave LISA its highest scientific ranking.

3

Mission Readiness and Cost Assessment

INTRODUCTION AND OVERVIEW

The “realism of preliminary technology and management plans, and cost estimates” is a primary assessment criterion called for in the statement of task for this study (see Appendix B). The assessment of the five Beyond Einstein mission areas against this criterion is necessarily comparative. Two specific criteria are used for the assessment: mission readiness and cost. The Committee on NASA’s Beyond Einstein Program assessed mission readiness in terms of the technical and management readiness challenges faced by the five Beyond Einstein mission areas. Technical readiness elements include the instrument, spacecraft, operations, and technical margins.[1] Management readiness elements include team organization, schedule, and other special challenges. The committee has attempted to assess the relative readiness of each candidate mission to proceed into mission development in fiscal year (FY) 2009. While a number of mission requirements and system design parameters were provided to the committee, the assessment was focused on those most germane to mission technical readiness. The cost assessment was done through an independent estimation of the probable cost.

For purposes of this study, “mission development” is defined as that point when the mission sponsor(s) commits to commence funding of the mission with the intent to proceed to flight. Technology readiness is a key consideration in the decision to proceed to mission development and, therefore, was a primary concern in the committee assessment of mission readiness. Ideally, mission development should not commence until all new technologies necessary for mission success have reached a Technology Readiness Level (TRL) of at least 6 (see the definitions of TRL levels given in the subsection below entitled “Technology Readiness and Degree of Difficulty”). Experience has shown that NASA and other missions pay the price when a mission enters development prematurely. In 2007, the National Research Council (NRC) recommended that “to enable an accurate assessment of science success and overall life-cycle costs, NASA should, in presenting potential missions to future survey committees, also distinguish between projects that are ready for implementation and those that require significant concept design or technology investment.”[2]

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[1] The terms “margins,” “allocations,” “reserves,” and “contingencies” are used consistent with definitions in recent announcements of opportunity, such as: “NASA Announcement of Opportunity, Mars Scout 2006 and Missions of Opportunity, May 1, 2006, Appendix B, Section G, #13.”

[2] National Research Council, *A Performance Assessment of NASA’s Astrophysics Program*, The National Academies Press, Washington, D.C., 2007, p. 42.

Unless otherwise cited, the information presented herein and the assessments of the committee were based on information supplied by the candidate mission teams in response to the committee's Request for Information (RFI) (see Appendix E) and the subsequent written answers provided in response to additional questions from the committee.

Disparity of Scale and Maturity

The five Beyond Einstein mission areas include two, Constellation-X (Con-X) and Laser Interferometer Space Antenna (LISA), that are of the scale of a Great Observatory, have a single mission concept, and were funded at the multimillion-dollar level over a number of years prior to the initiation of the study. The three probe mission areas, Black Hole Finder Probe (BHFP), Joint Dark Energy Mission (JDEM), and Inflation Probe (IP), are about one-third to one-half the scale of the other two. Each has multiple mission concepts and was funded at a variety of levels and over various time frames. Most of them received NASA funding of only $200,000 over 2 years, although one of the JDEM missions, Supernova Acceleration Probe (SNAP), has had substantial time and funding invested in its definition by the Department of Energy (DOE). This disparity of scale and maturity among the five mission areas is a fact that cannot be ignored in the assessment and is the key reason that the assessment must be comparative. Indeed, to try to normalize the missions in order to judge them against an absolute scale would mask the very information needed for a realistic assessment.

The spacecraft bus or particular spacecraft components are included in some of the instrument technology tables because the mission team included them it its technology listings. The committee decided to keep the same lists as those of the mission teams. In a few cases there was insufficient information to do a complete assessment of a particular mission concept within a mission area.

Technology Readiness and Degree of Difficulty

As part of the technical readiness assessment, the standard NASA definitions of TRLs were used in the assessments (see the list of definitions below).[3] TRL definitions are open to some interpretation and are often interpreted differently by different people (e.g., by technology or project personnel versus independent assessors). Because TRL overestimation has led to schedule and cost issues for many space programs in the past, the definitions were applied rigorously and conservatively in this assessment. That is, if there was any uncertainty in the assignment, the committee selected the more conservative (lower) TRL level or assigned a range (e.g., TRL 3-4). The normal NASA standard is that a TRL of 6 or higher should be achieved prior to proceeding into development.[4] The simplified definitions of TRLs that the committee used are as follows:

TRL 1. Basic principles observed and reported.
TRL 2. Technology concept and/or application formulated.
TRL 3. Analytical and experimental critical function and/or characteristic proof-of-concept completed.
TRL 4. Component and/or breadboard validated in laboratory environment.
TRL 5. Component and/or breadboard validated in relevant environment.
TRL 6. System/subsystem model or prototype demonstrated in a relevant environment (ground or space).
TRL 7. System prototype demonstrated in a space environment.
TRL 8. Actual system completed and "flight-qualified" through test and demonstration (ground or flight).
TRL 9. Actual system "flight-proven" through successful mission operations.

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[3] NASA, NASA System Engineering Processes and Requirements, NPR 7123.1A, March 26, 2007. Available at http:\\nodis3.gsfc.nasa.gov.

[4] Ibid.

For the degree of difficulty (DoD) of achieving at least TRL 6 prior to development, the committee used the five-level scheme used in past NASA literature (see below).[5,6] DoD estimates (not required from the mission teams) are also somewhat subjective. Again, the ratings assigned in this document are the best estimates of experienced technology developers working with information supplied by the candidate mission teams. Initial estimates were discussed with the full committee at the third committee meeting (see Appendix D), and were revised on the basis of the committee members' inputs and the latest inputs from the mission teams. As with the TRL estimates, the DoD ratings are considered to be conservative. The DoD definitions used in this assessment are as follows:

I. Very low degree of difficulty anticipated in achieving research and development (R&D) objectives for this technology; only a single, short-duration technological approach needed to be assured of a high probability of success in achieving technical objectives in later systems applications.
II. Moderate degree of difficulty anticipated in achieving R&D objectives for this technology; a single technological approach needed; conducted early to allow an alternate approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications.
III. High degree of difficulty anticipated in achieving R&D objectives for this technology; two technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications.
IV. Very high degree of difficulty anticipated in achieving R&D objectives for this technology; multiple technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications.
V. The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough in physics, chemistry, and so on is needed; basic research in key areas needed before system concepts can be refined.

Cost Assessment

A schedule and cost assessment was performed to provide an understanding of each Beyond Einstein mission's probable cost. The schedule assessment for each mission concept is contained in the individual discussions in the section below ("Mission Readiness Assessments"), while the cost assessments for each mission concept are given in the next major section ("Mission Cost Assessments"). Consistent methodologies were used to independently estimate cost and development time for the 11 Beyond Einstein mission concepts and to compare them with previous missions of similar scope and complexity. In order to provide a realistic expectation of the cost range for various Beyond Einstein mission classes, the independent estimates and the mission team's own proposed plans were considered. The committee also assessed life-cycle costs and potential funding profiles against the available NASA Beyond Einstein funding wedge[7] and non-NASA budget contributions as part of the considerations in making its recommendations.

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[5] James Bilbro and Robert Sackheim, "Managing a Technology Development Program," paper presented at the Workshop on Process for Assessing Technology Maturity and Determining Requirements for Successful Infusion into Programs, September 2003.

[6] John C. Mankins, "Research and Development Degree of Difficulty (R&D^3)" White Paper, Advanced Projects Office, Office of Space Flight, NASA Headquarters, Washington, D.C., March 10, 1998.

[7] NASA's FY 2007 budget request projected NASA's level of support for Beyond Einstein missions covering the years FY 2007 through FY 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 funding wedge."

MISSION READINESS ASSESSMENTS

Black Hole Finder Probes

CASTER Mission

CASTER Technical Challenges: Instrument There are multiple technology readiness issues with the Coded Aperture Survey Telescope for Energetic Radiation (CASTER), and it is clear that more technology development will have to occur on the detector, scintillators, coded aperture, and collimator shielding technique before the concept can be considered ready for mission development. Table 3.1 summarizes the CASTER technology readiness.

The Burle Planacon tube has been selected as the readout sensor for CASTER and similar photo-multiplier tubes (PMTs) have been used many times in space applications. The CASTER design, however, is not flight-rated, and the CASTER Request for Information response states: "We currently have no experience with this device." An alternate (the Hamamatsu H8500) is available, and the mission team considered it, but the Burle Planacon was chosen because it has the potential to be more rugged. The CASTER RFI also states: "A program to fabricate and test . . . would raise the TRL of this device to 5 or perhaps 6," but it does not appear that a concerted effort in this regard is in place. The CASTER design shows one of the Burle Planacon 8 × 8 detectors in each detector module, with 16 detector modules per "detector tile" and 9 or more detector tiles in the instrument. Based on these inputs, the detector TRL is rated as 2-3 and the DoD is rated as II-III. The mission team is pursuing more than one alternative.

The description of the coded aperture mask states[8] that "the combined requirement of fine angular resolution, wide FoV, and broad energy range places severe requirements on the parameters of the coded mask. In the case of CASTER, the requirements are more challenging than those of any coded mask that has been used in space (e.g., SIGMA or Swift)." Shielding, opaqueness, and other issues will need to be resolved. Further, in order to achieve the required sensitivity, CASTER will require a very large number of detector modules and will present manufacturing problems similar to those encountered in Swift. In the absence of additional information on the coded mask, the committee estimates of TRL and DoD are 2-3 and II-III, respectively.

The lanthium bromide ($LaBr_3$) scintillators are similarly in an early state of development. The material has been fabricated and some environmental testing has been done. A significant effort will be required to bring $LaBr_3$-based scintillators to TRL 6 from the committee's current rating of TRL 2-3. The DoD for the scintillators is judged to be III, based on both the existence of a known issue to be resolved (e.g., internal background) and unknown issues that may surface as testing of this low-maturity technology is conducted.

CASTER Technical Challenges: Spacecraft The CASTER observatory is extremely heavy and has a unique configuration, and the structure will present a serious technical challenge to design. In addition, little work has been done to date by any of the spacecraft contractors to accommodate the very large, very heavy CASTER instrument with the bus. The size, mass, long configuration, and associated high center of gravity location make it unclear that any currently available expendable launch vehicle (ELV) can accommodate the CASTER mission. Table 3.2 lists the requirements imposed on the spacecraft by the CASTER mission.

CASTER Technical Challenges: Operations In order to achieve the science goals discussed in Chapter 2, the spacecraft will primarily operate in a scanning mode. For CASTER's nominal scanning mode, the spacecraft is zenith pointed and the large field of view (FOV) of the imager array will cover a significant fraction of the sky every orbit. To further maximize the sky coverage, the spacecraft pointing direction will be continuously scanned (at a low scan rate) in a direction perpendicular to the orbital plane. The offset will be on the order of ±20°, with the spacecraft pointing direction moving either above or below the plane on successive orbits. The standard mode of instrument operation will be a mode in which individual processed events are transmitted to the ground. The telemetry stream in this case will also include housekeeping data and occasional raw event messages to monitor

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[8] Mark McConnell, University of New Hampshire, "CASTER, A Candidate Concept for the Black Hole Finder Probe," presentation to the committee, January 30, 2007.

TABLE 3.1 CASTER Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarity	Changes from Previous Mission/Comment	Program Rating	Committee Rating	Committee Rating
Detectors and light sensors	None known	N/A	Baseline approach identified: current laboratory prototype uses a Planacon tube by Burle Industries. Alternative is a Hamamatsu flat panel PMT.	3	2-3	II-III
Scintillator	Some use in medical industry, no known flight heritage	N/A	Lanthanum bromide (LaBr3) scintillator material has been developed and shows promise, but testing is in early stages.	4	2-3	III
Coded aperture	Swift, SIGMA	Basic design	Smaller and thicker mask than Swift. Complex mask and program literature indicate that the mask pattern has not been specified.	Not stated	2-3	II-III
Collimator shield	None known	N/A	Baseline design chosen and trade studies appear to be in early stages.	Not stated	2-3	II-III

NOTE: N/A, not applicable. Other acronyms are defined in Appendix G.

instrument health. In addition, this mode will include spectral accumulations from the shield elements, at some commandable integration time. Upon the receipt of a burst trigger signal, the instrument will be placed into a special burst accumulation mode (which has not yet been defined).

The onboard event processing will use raw events from a single module as input. The goal of the onboard processing will be to apply a camera imaging algorithm that reduces the 64 pulse-heights to an estimate of the location of the photon interaction site (x, y, and z). The mission team will be exploring various algorithms for high-rate processing of these data. One option is a neural-network-based algorithm. The mission team's experience using neural network algorithms for the processing of event location data from the Compton Gamma Ray Observatory's Compton Telescope will be of benefit here. Events with multiple interaction sites require special attention. First, these events must be recognized as such. Then they must be processed to make a determination of where the first interaction site was likely to have been. In the case of multiple interactions, it is the first interaction site that is of interest and that would be used to specify the (x, y, z) location. Events with multiple interaction sites would be flagged in the event message.

The CASTER operations are straightforward and not a significant challenge. The development of algorithms may be somewhat challenging, although the mission team's experience provides confidence that it will be done successfully.

CASTER Technical Margins The CASTER mission concept is still in an early conceptual stage, with only notional estimates for size, weight, power, and other performance parameters, making it difficult to thoroughly assess the margins of the proposed design. It is clear, however, that the CASTER mission will require a very heavy instrument and spacecraft. The CASTER team's current mass estimate totals 14,700 kg (13,740 kg [dry mass] + 960 kg [propellant]). Accommodating a spacecraft of this size to the desired orbit (500 km circular orbit at 0° inclination) will be challenging. As the orbit inclination increases, passage through the South Atlantic Anomaly (SAA) will both reduce the available observing time and introduce an increased level of background. Although SAA passages are tolerable, the ideal orbit would be an equatorial orbit to eliminate the SAA passages and maximize the geomagnetic rigidity. An equatorial orbit also provides a low background for high-energy x-ray and gamma-ray missions. However, the proposed launch vehicle, a Delta IV-Heavy, cannot achieve this inclination. This launch

TABLE 3.2 CASTER Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	About 1° control, about 5 arcmin knowledge	No challenge
	Tracking	0.5 deg/min	No known requirement
	Jitter/stability	1 deg/s	No challenge
Power	Orbital average	1,370 W, payload 550 W, spacecraft 480 W contingency	Drives array size
	Worst case	2,240 W—total bus	Array size
Data storage	—	6.4 GB (4 orbits)	No challenge
Structure	Payload	8,950 kg	Extremely large vehicle, very heavy launch loads; only notional illustrations shown on arrangement of payload in spacecraft bus
	Spacecraft	2,500 kg	
	Contingency	2,290 kg	
	Total	13,740 kg	
	Margin	6,860 kg	
Thermal	—	Not specified	Unknown
Radio-frequency communications	Downlink	Average data rate: 2.2 Mbps 200 Mbps downlink via TRDSS Ka band	Unknown if this rate is available
	Uplink	Not specified	Unknown
Alignment	—	Not specified	Unknown
Propulsion	Delta-V	Required delta-v (velocity increment) is unknown; 800 kg propellant allocated in mass tables.	Unknown

NOTE: Acronyms are defined in Appendix G.

vehicle would be able to reach an inclination of 15° with zero mass margin and could comfortably reach a 28° inclination with more than 50 percent margin. It is possible that a non-U.S. launch vehicle could have the capability to launch CASTER into the desired orbit; however, the use of a non-U.S. launcher would require approval through an interagency policy coordination process.

CASTER Management Challenges If selected, the CASTER team will be led by a principal investigator from the University of New Hampshire, with project management support from Southwest Research Institute (SwRI). Key team members are from Louisiana State University; the University of Alabama, Huntsville; the Los Alamos National Laboratory; and the University of California, Berkeley. This is a modest-sized team, and the management of the team itself presents no special problems. However, owing to the number and seriousness of issues associated with this mission, the technical management could be quite challenging. There is no known significant foreign contribution planned for CASTER, thus lessening International Traffic in Arms Regulations (ITAR) problems and eliminating the mission's vulnerability to foreign government priority changes.

The CASTER mission schedule shows launch 4.5 years after the preliminary design review (PDR), which is tight even if progress is made by the mission in raising the TRLs of the elements listed in Table 3.1. The critical path, predictably, is through the test program of the flight instrument. It was not possible to determine how much reserve is included in the proposed schedule. Completing the technology development and detector production activities will pose a significant schedule risk for the project.

CASTER Unique Challenges Technology development related to the detector system and the huge mass and size of the assembled instrument are the main challenges to CASTER.

EXIST Mission

EXIST Technical Challenges: Instrument The High Energy Telescope (HET) cadmium-zinc-telluride/application-specific integrated circuit (CZT/ASIC) and Low Energy Telescope (LET) silicon detector/readout electronics are not expected to be major engineering challenges for the Energetic X-ray Imaging Survey Telescope (EXIST) mission. Heritage from other programs exists, but the technology requirements are more complicated than what has been demonstrated in the past, and packaging the electronics will be challenging. Significant development work is being pursued, and a successful demonstration on the ProtoEXIST1 flight planned for 2008 should raise the TRL for the HET and demonstrate readout and postprocessing electronics for both the CZT and silicon (Si) detectors. There is still development work to be done to reach a full TRL of 4. The yield on 64 pixel ASICs has been about 40 percent, and it does not appear that a 256 pixel unit has been fabricated or tested. The HET array and processing are more complicated than what has been used in the past, but the heritage and the descriptions given of ongoing efforts suggest that the development effort will be reasonable, and the DoD is rated II. The LET Si hybrid pixel detector has heritage from other programs, but EXIST requires several departures from these existing systems. The mission team's response to the committee's RFI notes that "some development is underway through a separate NASA Phase 1 SBIR." This indicates that the TRL is low, and the committee has assessed it at 3. The heritage suggests that the DoD should not be high (DoD = II). The LET electronics are similar to those of the HET, and a successful ProtoEXIST flight combined with ongoing development efforts should raise the TRL in 2008. The technology readiness for EXIST is illustrated in Table 3.3.

TABLE 3.3 EXIST Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
High-energy detectors (19 telescopes)	ProtoEXIST imager—balloon. Swift/BAT	Basic design, materials	Coded mask telescopes and shielding: components demonstrated in laboratory; the departure from the current state of the art is minimal. Both Cd-Zn-Te (CZT) array and readout electronics are more complicated than proven systems. Planned ProtoEXIST flight in 2008 should raise TRL.	5-6	3-4	II
Low-energy detectors (32 telescopes)	Commercial product	Unknown	Uses Si detectors for the Low Energy Telescope (LET). Larger pixels, spectrographic readout of each pixel. Prototype developed under SBIR by Black Forrest Engineering.	3	3	II
Coded-aperture telescope	SIGMA—Russian INTEGRAL-ESA	Unknown	5 mm tungsten mask for the High Energy Telescope (HET). New laminate required for pinhole pattern.	<4	3	II-III
Shielding/anti-coincidence system	None	Not applicable	Uses cesium iodide (CsI) scintillators with PMTs and light pipes around CZT detectors.	<4	3	II

NOTE: Acronyms are defined in Appendix G.

The coded-aperture mask technology is based on prior work and requires a laminating technique. While this is relatively new, the technique has been demonstrated in the laboratory. The pinhole pattern and the actual laminate construction of the masks for the two types of telescopes will require significant development. Based on this, the committee's estimates of the coded-aperture mask technology are 3 and II-III, respectively.

The shielding/anticoincidence system also presents a challenge. Both passive and active shielding will be used. The dimensions are large, and fabrication and packaging will present issues. While the current TRL is judged to be low (TRL = 3), no major obstacles are foreseen, and the DoD for the shielding is judged to be II.

The manufacturing of the large number of subsystems will also be a challenge. In addition, the On-board Burst Alert system has to be developed and debugged. This system will be a driver to the spacecraft attitude determination and control (AD&C) system.

EXIST Technical Challenges: Spacecraft Spacecraft accommodation requirements for EXIST are listed in Table 3.4.

EXIST Technical Challenges: Operations EXIST is a full-sky imaging mission performing a survey in the 10-600 keV and the 3-30 keV energy range every 90 minutes. The HET and LET are composed of 19 and 32

TABLE 3.4 EXIST Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	1 arcmin control 5 arcsec knowledge	No challenge
	Tracking	15° nodding	Unknown
	Jitter	~15° nodding scan	No challenge
Power	Orbital average	1,912 W payload with 30% contingency 957 W bus with 9% contingency 2,869 W with 22.1% contingency	Drives array size
	Worst case	1,912 W	Array size
Data Storage	—	18 GB	Cost
Structure	Payload	6,339 kg/20% contingency	Size, cost
	Bus	2,451 kg dry mass	Size, cost
	Total/margin	9,709 total wet mass/3,191, 32.7 on Atlas 551	Appears satisfactory; good margin but expensive expendable launch vehicle.
Thermal	—	Not specified	Unknown
Radio-frequency communications	Downlink	5 Mbps science data rate 200 Mbps via TDRSS	TDRSS access time required.
	Uplink	TDRSS	No challenge
Alignment	—	None	No challenge
Propulsion	Delta-V	260 m/s for orbit maintenance and disposal. Pressurized bipropellant design.	Mass, cost, safety

NOTE: Acronyms are defined in Appendix G.

subtelescopes, respectively, and each subtelescope of the HET and LET has 21° × 21° and 16° × 16° fully coded FOVs, respectively. The satellite is zenith-pointed with the fan beam perpendicular to the orbital direction, and the satellite executes a continuous sinusoidal "nodding" motion with amplitude +/−15° perpendicular to the orbital ram to dither the fan beam ends between the two orbital poles to cover the full sky during each orbit.

The EXIST instruments handle and record each x-ray event one by one. The event data stream goes into two independent parallel processing channels: (1) the event collecting system and (2) the Fast On-board Burst Alert System (FOBAS). Both the HET and the LET perform these two processes independently. In the event collecting system, each valid event will be time-tagged and recorded. These data will be telemetered to ground by the Tracking and Data Relay Satellite System (TDRSS) Ku band (200 Mbps limit) with six contacts per day of about 6 minutes each.

EXIST flight operations and data processing parallel the Swift mission experience. While this provides assurance that EXIST flight operations and data processing are not particularly challenging, the higher data rates involved may make the onboard and ground processing more demanding.

EXIST Technical Margins The proposed EXIST spacecraft is in the conceptual stage, with some basic design trade studies completed. The EXIST mission concept appears to have good technical margins for size, weight, power, and other performance parameters, consistent with the maturity of the overall system concept. EXIST is a relatively heavy spacecraft (9,700 kg wet) and would ideally be flown in an equatorial orbit (0° inclination). However, because of the performance limits on available launch vehicles, the EXIST mission will be flown in a 20° inclination orbit.

EXIST Management Challenges The EXIST team is led by a principal investigator at Harvard University and the Harvard-Smithsonian Center for Astrophysics and includes team members from Goddard Space Flight Center (GSFC); the University of California, San Diego; the University of California, Berkeley; Yale University; Cambridge University; Marshall Space Flight Center (MSFC); and many other institutions. It is expected that the management support will be from GSFC since it has been so deeply involved with EXIST for the past few years. There are no unusual project management challenges other then the schedule, as discussed below.

The proposed schedule shows 4.25 years from PDR to launch. This is judged to be quite tight, given the extent of the detector-production effort and the roll-up of instrument assembly into an observatory.

EXIST Unique Challenges The large weight of EXIST requires a large and expensive expendable launch vehicle. Mass reduction is a particular challenge that EXIST faces if it is to be affordable.

Constellation X-Ray Observatory

Con-X Technical Challenges: Instruments

This subsection describes the technology readiness of the Con-X mission, with special consideration given to the readiness of the microcalorimeters and the x-ray optics. The Con-X team has had several years to develop these key technologies and as a result produced multiple breadboards and prototype units to use in quantifying performance and reducing risk. Table 3.5 is a summary of the Con-X technologies and their current state of development. There are multiple technologies with a TRL of 5 or lower that present challenges for the mission if it is to be ready to begin development in 2009. The length of the list is due in part to the thoroughness of the Con-X team, which has been careful to identify all new technologies necessary for the mission.

The Con-X observatory employs two telescope systems: the Spectroscopic X-ray Telescope (SXT) and the Hard X-ray Telescope (HXT).

The design of the Flight Mirror Assembly (FMA) optics used in the SXT is driven in large part by the need for large collecting area and high angular resolution. Key parameters of each of the four SXT optics are listed in Table 3.6.

TABLE 3.5 Con-X Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
SXT FMA mirror fabrication	Einstein, ROSAT, ASCA, Chandra, XMM-Newton, HEFT, Suzaku	Wolter Type I optics, thin mirror segments (ASCA, Suzaku), mass production (ASCA, Suzaku), mandrel fabrication (XMM-Newton), hundreds of co-aligned mirror segments (ASCA, Suzaku), moderate angular resolution (XMM-Newton), areal density (Suzaku, HEFT).	Combine angular resolution demonstrated by XMM-Newton with number of mirror segments and a real density demonstrated on Suzaku and HEFT.	4	3-4	II
SXT FMA mirror assembly	Chandra	Many more mirror segments than Chandra but alignment budget less demanding.	Over 2,000 individual segments to be aligned. Two methods being evaluated.	3	3	III-IV
XMS-micro-calorimeter	XQC suborbital payload, Suzaku-XRS	Microcalorimeter technology, wafer processing, operating temperature, ADR technology, data processing.	Increased pixel count, multiplexed readout, cryogen-free operation.	4	4	II
XMS-ADR	XQC suborbital payload, Suzaku-XRS	Same basic technologies as XRS-ADR. Con-X requires broader operating range and increased cooling capacity because of the larger arrays. Continuous operation is anticipated.	Multistage ADR, passive heat switches, somewhat more complex control algorithm. Multiple component demonstrations completed.	4-5	4-5	II
XMS-cryo cooler	Under development for JWST	Low vibration, minimum power.	Possibly use ^{3}He instead of ^{4}He to achieve lower operating temperatures. Joint development effort with JWST and TPF: three alternatives being pursued.	5	4-5	II
XGS-grating	Sounding rockets, Einstein, Exosat, Chandra, XMM-Newton	Basic fabrication techniques, alignment tolerances, number of grating elements, data analysis. Both line density and facet size are increased compared to prior applications.	Required technology advances (line density, facet size) have been demonstrated separately; a flight prototype is to be developed and tested in 2008.	4	4	II

continued

TABLE 3.5 Continued

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
XGS-CCDs	ASCA, Chandra, XMM-Newton, Suzaku	Number and size of basic fabrication processes, backside thinning, data processing and analysis.	Low-energy QE requires backside processing different from that for prior devices. Modeling suggests that QE requirement can be met, but testing has not been performed.	4	3-4	II
HXT-optics	Swift, InFocus, HEFT, HERO	Highly nested, graded multilayer coated mirrors for 10-40 keV (InFocus, HEFT). Electroformed thin Ni shells (HERO, Swift). Thermally formed segmented glass mirrors.	Basic processes demonstrated, but not to the requirements of Con-X. Two processes being developed under funding outside of the Con-X program.	5	3-4	II
HXT-detector	Swift, InFocus, HEFT, HERO	Number and size of pixels, basic fabrication processes, data processing and analysis.	Improved shielding design and fabrication.	5.5	4	II

NOTE: Acronyms are defined in Appendix G.

TABLE 3.6 Key Parameters of Each Spectroscopic X-ray Telescope (SXT) Flight Mirror Assembly (FMA)

Parameter	Value
Band pass	0.3-10 keV
Angular resolution	12.5 arcsec half power diameter
Effective area at 1.25 keV (on-axis)	4,610 cm^2
Field of view	≥7 arcmin diameter
Optical design	Segmented Wolter I
Diameter (largest/smallest mirror surface)	1.3 m/0.3 m
Mirror segment material	Thermally formed Schott Desag D263 glass
Number of mirror segments per FMA	10 (outer); 5 (inner)
Number of mirror pairs per module	97 (outer); 66 (inner)
Largest mirror segment surface area	0.08 m^2

The FMA consists of 15 modules: 5 identical inner modules subtending a 72° arc and 10 identical outer modules subtending a 36° arc. The complete FMA will contain 2,600 mirror segments. The mirror segments will be assembled from thermally formed glass substrates coated with an iridium reflecting surface. Fabrication of all of these mirror segments, verification of their optical performance, and proper mounting and alignment of the segments will be challenging.

The mission team argues that the SXT design is based on materials that are highly reflective (iridium) and that the wedge mandrels are producible and readily procured. Mirror accommodation studies are on record going back to 2005 for launch on a single Delta IV Heavy and in 2006 for a single Atlas V. A mirror fabrication study was undertaken by Swales Corporation in March 2003. According to the mission team, the report concluded that

TABLE 3.7 Key Studies Performed on the Spectroscopic X-ray Telescope (SXT) Flight Mirror Assembly

Date	Study Title	Results
2003	Alternative mirror prescription	Apparently concluded that the Wolter Type I design was the best for the mission.
2003	Impact of mirror focus correction on imaging performance	Evaluated limits of allowable focus correction achieved by warping the thin mirrors to change their cone angle. Warping worked.
March 2003	Fabrication study by Swales Corporation	Concluded that the telescope could be built within the program's allocated time.
October 2005	Delta IV heavy mirror design study	Achieved comparable effective area performance with multiple mirror configurations demonstrating the robustness of the design.
August 2006	Off-axis mirror performance	Design's off-axis performance is acceptable.
September 2006	Design for 3 and 4 SXT single spacecraft Atlas V launch	Evaluated multiple three- and four-mirror designs, concluded that a four-mirror design could be accommodated on the Atlas V with the added advantage that fewer mandrels and mirror surfaces were required over the three-mirror configuration.

TABLE 3.8 HXT Mirror Performance Requirements

Parameter	Value
Band-pass	6-40 keV
Effective area	150 cm^2
Angular resolution	30 arcsec half power diameter

"the telescope could be built in the required time interval based on the mission level schedule."[9] In August 2006, a performance evaluation was conducted on the off-axis performance and found that there was little degradation in performance of the proposed design off-axis to meet a performance goal of 15 arcsec. Table 3.7 summarizes all of the studies and evaluations performed on the SXT.

According to the mission team, the FMA defines the critical path of the project. The assembly will be designed, fabricated, and assembled by industry through a competitive procurement. Although a good deal of detailed planning for the FMA has been performed by the mission team, it is not obvious how much of this planning will transfer to the contractor that will be selected to produce the FMA. While the Con-X plan calls for involving the contractor in the final phase of technology development, procurement regulations could make this difficult. It is also unclear how well the considerable experience of the Con-X team in designing the FMA components will transfer to the selected contractor. The planned time for the development of the SXT FMA is stated to be approximately 3.5 years.

The performance requirements for each of the two HXT mirrors are given in Table 3.8.

According to information provided to the committee, the feasibility of imaging hard x-rays has been demonstrated by multiple balloon programs (e.g., International Focusing Optics Collaboration for micro-Crab Sensitivity [InFOCUS], High-Energy Replicated Optics [HERO], and High Energy Focusing Telescope [HEFT]). A technology readiness implementation plan was written in 2003 and updated after the decision was made to shift to the Atlas 5 ELV. An RFI was issued by the mission team in October 2006 for instrument concepts for a hard x-ray telescope. No other information was found in documentation provided to the committee on the Con-X team's plans for production of the HXT.

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[9] Constellation X-Ray Observatory team response to the committee's Request for Information (see Appendix E in this report), January 2007.

The SXT instrument depends on the availability of the X-Ray Microcalorimeter Spectrometer (XMS). The mission team states that a major benchmark for the XMS was the flight of the Suzaku observatory in 2005. Microcalorimeters have been in use for x-ray spectroscopy since 2002, when the first such detector was flown on a sounding rocket for measuring the diffuse x-ray background.[10] The Con-X team has fabricated and demonstrated the performance of an 8 × 8 transition edge sensor (TES) array with 250 m pixels. For flight, a 32 × 32 array is required. A major challenge is the readout electronics associated with the detectors. In particular, sampling speed and the requirement for a very low noise figure are key design drivers for the readout electronics.

Con-X has technology readiness challenges with all of the devices listed in Table 3.5 with TRLs of 5 or lower. Of particular concern, however, is the development of the microcalorimeters, since the success of the mission is dependent on these detectors. The mission team states that it believes that its top mission risks are (1) mirror angular resolution, (2) XMS field of view, and (3) XGS/HXT accommodations.

Con-X Technical Challenges: Spacecraft

The SXT and HXT instruments drive multiple spacecraft design and performance requirements. Table 3.9 shows the instrument accommodation requirements on the spacecraft and, where appropriate, impacts associated with instrument accommodation.

Con-X Technical Challenges: Operations

Constellation-X operates as a queue-scheduled observatory, pointing at selected targets in the most time-efficient way consistent with science and observatory constraints. Each of the Con-X instruments has a science and engineering mode of operation. For the X-ray Microcalorimeter Spectrometer, the instrument science modes include submodes to allow the adiabatic demagnetization refrigerator (ADR) to reach operating temperature and a second mode to maintain the operating temperature while acquiring science data. There are no other XMS science modes.

For the X-ray Grating Spectrometer (XGS), science modes include (1) timed exposure (TE): photons are collected in a frame for a selectable exposure time before being read out, and (2) continuous clocking (CC): where the charge-coupled device (CCD) is read out continuously; each output pixel represents the integrated flux received as the charge crosses the array. The instrument also has diagnostic, calibration, and engineering modes. For the Hard X-ray Telescope instrument, the operating modes include imaging, calibration, and engineering modes of operation. The application of Chandra experience provides confidence that the Con-X operations will not be a particular challenge.

Con-X Technical Margins

The Con-X mission has adequate technical margins in most areas. The Con-X mission includes 30 percent contingency on its mass estimate and about 1 percent margin on the launch vehicle performance. The 1 percent mass margin for the launch vehicle may not be sufficient for the project. Given that important aspects of the Con-X instrument design are still being evaluated and that ongoing trade studies could result in an increase in mass, overall mass management for Con-X is critical. Particularly, the Con-X team identified XGS and HXT accommodation as an open trade that could result in increased mass. While descoping options have been identified, they would entail significant science loss. Alternatively, Con-X could choose a larger launch vehicle to increase its margin, but at a higher cost. Continued close management of weight growth is necessary for a program at this stage.

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[10] D. McCammon, R. Almy, E. Apodaca, W. Bergmann Tiest, W. Cui, S. Deiker, M. Galeazzi, M. Juda, A. Lesser, T. Mihara, J.P. Morgenthaler, W.T. Sanders, J. Zhang, E. Figueroa-Feliciano, R.L. Kelley, S.H. Moseley, R.F. Mushotzky, F.S. Porter, C.K. Stahle, and A.E. Szymkowiak, 2002, A high spectral resolution observation of the soft x-ray diffuse background with thermal detectors, *Astrophys. J.* 576:188-203.

TABLE 3.9 Con-X Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	Pitch: 10 arcsec Roll: 30 arcsec Yaw: 10 arcsec	None; well within the state of the art for a conventional spacecraft design
	Tracking	1 arcsec/100 microseconds	Unknown
	Jitter	<2 arcsec/13.8 milliseconds	No challenge
Power	Orbital average	Approx. 2,345 W	Array size and battery size
	Worst case	3,351 W peak	Drives solar array size
Data storage	Orbital average	18 GB	No challenge; systems commercially available
Command and data handling	CPU	Not specified	Unknown
	I/O	Not specified	Unknown
Structure	—	Approx. 1,000 kg payload with 30% contingency. Approx. 2,398 kg bus with 30% contingency, 335 kg propellant with 30% contingency	Leaves only 88 kg margin on Atlas V 551. Appears to be a problem.
Thermal	FMA	10°C to +30°C	3.5 m^2 of radiator area required to maintain payload operating temperatures. Worst case 2,500 W required for survival heaters. Multiple local thermal controls required to maintain detectors and optics at different temperatures. Wide range of operating and survival temperatures.
	XMS	−30°C to 70°C	
	XGS	Varies with component	
	HXT	−100°C to +30°C for detector	
Radio-frequency communications	Downlink	3.5 Mbps	No challenge
	Uplink	Minimal	No challenge
Alignment	—	Multiple requirements from 10 arcsec up	No challenge

NOTE: Acronyms are defined in Appendix G.

Con-X Management Challenges

The Con-X team is led by GSFC, with the mission scientist at the Smithsonian Astrophysical Observatory (SAO). There are no special project management challenges for Con-X. The team has little dependence on non-U.S. team members. In addition, the team has worked together for several years, and any institutional interface issues have long since been resolved.

The schedules supplied to the committee were technology development schedules. No overall mission development schedule was provided. Since the spacecraft bus is well within the state of the art, it seems reasonable to assume that the mission critical path will be through the SXT and associated detector assembly.

Inflation Probes

CIP Mission

CIP Technical Challenges: Instrument The Cosmic Inflation Probe (CIP) mission generally makes use of available technologies or technologies being developed for other programs (e.g., the James Webb Space Telescope [JWST]). There are no significant technology challenges for CIP, although work remains to be done to see if the detector noise figure is adequate at the planned higher operating temperature. The technology readiness of the CIP mission is illustrated by Table 3.10.

CIP uses an all-reflective three-mirror anastigmatic optical design. The optical figure of the required components is within the state of the art and should present no special challenges.

The detector uses the Teledyne Hawaii-2RG HgCdTe detectors currently planned for JWST, operating at a somewhat higher temperature. The major outstanding issue is whether the dark current level is acceptable at the higher temperature. The vendor (Teledyne Brown) is planning to test the dark current levels at the higher temperature using JWST hardware and, assuming that the levels are acceptable (predicted from early laboratory tests), the degree of difficulty should be low (DoD = I-II). The current TRL is judged to be 4, but this should rise rapidly following the JWST hardware testing.

The spectrometer's focal plane array (FPA) and ASIC are below TRL 6 (TRL judged to be 5), but both are similar to JWST equipment and neither should have a DoD of more than I, assuming that JWST development is successful. Additional development of the grating technology would be beneficial.

CIP Technical Challenges: Spacecraft There are no unusual or challenging accommodation requirements for CIP relative to the spacecraft. Spacecraft accommodation requirements for the CIP mission are listed in Table 3.11.

CIP Technical Challenges: Operations CIP will conduct operations at Lagrange Point 2 (L2) for 3 years in order to meet mission baseline requirements. The mission team provided very little by way of operations information. As a redshift survey mission, its operations are expected to be similar to other survey missions in complexity. Since

TABLE 3.10 CIP Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
Detectors	JWST/ NIRSpec, NIRCAM, and FGS	Basic design and construction	Uses 8k × 8k Teledyne Hawaii-2RG HgCdTe detectors. CIP will operate at a warmer temperature than JWST. Will need characterization of noise at higher temperature.	6 (at completion of noise characterization)	4	I-II
Optics	ATT/ JWST, NextView	Similar material and configuration	Uses all reflective three-mirror anastigmatic (TMA) at f/14.4.	6-7	6	Not applicable
Spectrometer	XSS-11	Similar to the Offner magnification all-reflective imaging relay	Uses slitless concentric wide FOV imaging grating spectrometer. The focal plane array and ASIC are similar to components being developed for JWST, and the other components appear to be at TRL 6.	5-6	5	I

NOTE: Acronyms are defined in Appendix G.

TABLE 3.11 CIP Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	2.5 arcsec/control 2 arcsec knowledge	No challenge
	Tracking	Not specified	Unknown
	Jitter	10 arcsec/500 s	No challenge
Power	Orbital average	540 W EOL 190 W payload 653 W EOL capability—100 W EOL margin	No challenge
	Worst case	Not specified	Unknown
Data storage	—	20 GB	No challenge
Structure	Payload	929 kg	No challenge
	Bus	357 kg plus propulsion module of 122 kg	No challenge
	Total/margin	1,655 kg/246 kg. 17.5% above allocated mass.	None; acceptable margins
Thermal	—	Passive with blankets and heaters	No challenge
Radio frequency communications	Uplink	2 kbps at S band	No challenge
	Downlink	100.5 Mbps at Ka band	No challenge
Alignment	—	Not specified	Unknown
Propulsion	—	1,956.3 m/s	Drives mass and complexity of observatory

NOTE: Acronyms are defined in Appendix G.

CIP uses passive cooling techniques, its operations are somewhat less complex than missions consuming cryogens with ever-changing center of gravity and balance issues. Flight operations of CIP should present no special challenges. Downlink data rates are somewhat high but well within the current state of the art.

CIP Technical Margins The CIP mission team provided a complete package of information that addressed each of the major technical areas. The team allocated adequate technical margins in most areas but did not provide margins for attitude control and data link. Given that the required performance in these areas is not stressing the state of the art, it does not raise significant risk issues.

CIP Management Challenges The CIP mission is led by a principal investigator from the Harvard-Smithsonian Center for Astrophysics. Team members include scientists from the University of Texas, the California Institute of Technology, the Jet Propulsion Laboratory (JPL), Lockheed Martin, ITT Space Systems, and Teledyne Scientific and Imaging. CIP is managed by the Smithsonian Astrophysical Observatory, with strong support from Lockheed Martin. Since there is no significant dependence on non-U.S. team members to contribute resources, there are no apparent project management challenges other than the schedule, described below.

The proposed schedule shows a PDR in the first quarter of 2010 and a launch in the second quarter of 2013. This is an extremely aggressive schedule, but the mission team claims that it has 5 months of schedule reserve. The schedule to the proposed launch date will be a challenge.

CMBPol Mission

CMBPol Technical Challenges: Instrument The microwave optics for the Cosmic Microwave Background Polarimeter (CMBPol) use a variable-delay polarization modulator (VPM) and a folding mirror to control the entry of stray light into the cooled detector array. The components appear to be standard microwave technology, but there is concern with noise in the detectors and readout electronics as well as some concern with the ability to couple the polarized optical signals. Project documentation indicates that similar VPMs (operating at higher and lower frequencies) have been prototyped at GSFC and are under evaluation. Based on this statement, the committee estimates the TRL to be 2-3, but the DoD cannot be judged without more information. The technology readiness for the CMBPol mission is shown in Table 3.12.

The detectors are the same TES detectors proposed for the other Inflation Probe microwave instruments. GSFC has experience with these detectors on previous missions. CMBPol's challenge will be to keep the noise low enough to make the measurement. There appears to have been a good deal of thought put into the detailed design and fabrication of the microwave strip line circuitry and the TES detectors and readout electronics. The CMBPol team has expressed some concern about the detailed design of the detector system, using the words "requires very innovative design" in describing the work to be done. This is an area in which an investment of time and money could potentially be put to good use. The TRL and DoD cannot be assessed on the basis of the information provided.

CMBPol Technical Challenges: Spacecraft A summary of the CMBPol mission spacecraft accommodation requirements is shown in Table 3.13. Not much was presented to the committee by way of spacecraft accommodation information.

TABLE 3.12 CMBPol Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
Cryocooler	Unknown, but refers to a pulse tube cooler developed by Lockheed Martin.	Unknown	Unknown	Not provided	Not enough information to assess	Not enough information to assess
Detectors	TES used in ACT, GBT	Unknown	Requires 1,000 TES detectors cooled to 100 mK. Requires 80 dB of noise reduction. Uses superconducting SQUID multiplexer/readout electronics.	Not provided	2-3	Not enough information to assess
Feed horn array	Unknown, but this is standard microwave technique.	Unknown	Uses Platelet feed horn array. Conventional microwave technology.	Not provided	Not enough information to assess	Not enough information to assess
Optics	HHT	Unknown	Uses variable-delay polarization modulator as first element for control of stray light. Folding mirror transfers radiation to detector array. Issues with polarization. Noted that prototypes operating at different frequencies have been built at GSFC.	Not provided	Not enough information to assess	Not enough information to assess

NOTE: Acronyms are defined in Appendix G.

TABLE 3.13 CMBPol Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	Not provided	Unknown
	Tracking	Not provided	Unknown
	Jitter	Not provided	Unknown
Power	Orbital average	Not provided	Unknown
	Worst case	Not provided	Unknown
Data storage	Payload	Not provided	Unknown
Structure	Payload	Not provided	Unknown
	Bus	Not provided	Unknown
	Total	Not provided	Unknown
Thermal	—	Not provided	Unknown
Radio frequency communications	Downlink	1 Gb per orbit	Unknown
	Uplink	Not provided	Unknown
Alignment	—	Not provided	Unknown
Propulsion	—	Not provided	Unknown

CMBPol Technical Challenges: Operations CMBPol is a slowly spinning all-sky survey mission. Very little was presented to the committee by way of details on flight operations for this mission. The material submitted states that the mission is still in conceptual development, so it is not surprising that operational details were not provided.

CMBPol Technical Margins Insufficient information concerning the spacecraft and mission concept was provided to the committee to allow an assessment of the technical margins of the CMBPol concept.

CMBPol Management Challenges CMBPol was presented as a mission concept only; no detailed schedule was made available. The mission team is led by a principal investigator at NASA GSFC, with team members from the University of Pennsylvania, the University of Chicago, Princeton University, Harvard University, the University of Toronto, and the University of California, Los Angeles.

CMBPol Unique Challenges The dearth of information on CMBPol and the absence of any statement invoking proprietary concerns indicate that it is in the very early stages of concept development. The committee assesses that CMBPol faces a major challenge and is very unlikely to be ready for mission development in 2009.

EPIC-F Mission

EPIC-F Technical Challenge: Instruments Antenna development for the FPA appears to be the major technology issue for the Experimental Probe of Inflationary Cosmology (EPIC-F) at this point. Integration of the cryogenic optics with the detector system to achieve the required low noise operation will also be challenging. The technology readiness summary for the EPIC-F mission is shown in Table 3.14.

Project documentation indicates that the wave plate technology planned for use in the microwave optics of EPIC-F has been matured to TRL 6 in ground testing. The information provided in the mission team's response to the committee's RFI suggests significant heritage, but this is not described. Without more information it is not

TABLE 3.14 EPIC-F Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarity	Changes/Comments	Project Rating	Committee Rating	Committee Rating
Focal plane array components (NTD Ge bolometers)						
NTD thermistors and JFET readouts	Planck and Herschel	Noted as identical to those of Planck and Herschel	None	8	>6[a]	N/A
Antennas	Ground demonstrations	Basic technology design	Different (wider) frequency range required.	4	3-4	I-II
Wide-field refractor	BICEP	Noted as identical	BICEP was ground tested at the South Pole.	6	6	N/A
Wave plate technologies						
Wave plate optics	SCUBA, HHT, MAXIPOL, others	Not provided	Noted that half-wave plates have significant ground testing.	6	5-6	I
Cryogenic stepper drive	Spitzer	Apparently identical	Noted that the stepper motor has been flight tested on Spitzer.	9	>6	N/A
Liquid helium cryostat	Spitzer, ISO, Herschel	Based on Spitzer design	Not enough information provided, but likely close enough to Spitzer design to make this low risk.	9	>6	N/A
Sub-K cooler: single-shot ADR	Suzaku	Project documentation indicates that this is the same as flown on Suzaku.	Little information provided.	9	>6	N/A
Deployable sunshield	JWST	Similar technology	Less complex (3-layer, 8 meter) than JWST (5-layer, 22 meter). All components should be at high TRL (project indicates 9).	4-5	4	I-II
Toroidal-beam downlink antenna	Multiple	Components are proven technologies.	No integrated demonstration.	4-5	3-4	I-II

NOTE: HHT, Heinrich Hertz Telescope; N/A, not applicable. Other acronyms are defined in Appendix G.

[a] A rating of TRL >6 reflects a lack of information about the exact application and environment for those items relative to their claimed flight heritage.

possible to put this technology at TRL 6, but the engineering and demonstration should be straightforward; the DoD is estimated at I. The basic principles for the antennas have been demonstrated, but EPIC-F requires a wider frequency range than has been demonstrated in the past. Laboratory experiments are promising, but both environmental and system testing are required.

The neutron transmutation doped (NTD) Ge bolometric detectors are not considered to be a serious challenge. Previous missions have used these detectors. Packaging may be a challenge for all missions planning on using these detectors to keep the noise to an acceptable level.

The deployable sunshield will require careful design and testing. It is similar to but much smaller than the one being developed for JWST. While the TRL is relatively low (TRL = 4), the engineering should be straightforward; the DoD is judged to be I-II. Similarly, the downlink antenna is a new design, but all of the components are of very high TRL. Because there has not been an integrated test, the TRL is judged to be low, but no major obstacles are anticipated for the development effort; the DoD should be between I and II.

EPIC-F Technical Challenges: Spacecraft Spacecraft accommodation requirements for the EPIC-F mission are listed in Table 3.15. The spacecraft requirements for this mission appear to be modest and are not expected to be a challenge.

EPIC-F Technical Challenges: Operations The six cooled telescopes that form the heart of EPIC-F are mounted to a spinning platform orbiting at L2 and use the spinning motion of the spacecraft to scan 50 percent of the sky on a daily basis, although 6 months of operation are required to complete a full-sky map. Owing to the consumption of cryogens and the operation of the active and passive cooling systems and the spinning motion of the bus, EPIC-F is likely to be somewhat complex to operate and to be operator labor-intensive. The low data rate requirement is a plus in reducing complexity.

TABLE 3.15 EPIC-F Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	1° control, 30 arcsec knowledge	No challenge
	Tracking	None	Not applicable
	Jitter	Stability of spin axis assumed to be 1°	No challenge
Power	—	272 W payload with 43% contingency 981 W bus with 43% contingency	GaAs triple junction cells, good margins.
Data storage	—	2 GB	No challenge
Structure	Payload	898 kg with 43% contingency	No challenge
	Bus	713 bus dry mass with 43% contingency; appears to be 1,783 wet mass of the total observatory	No challenge for the planned Atlas V 401 of Delta IV 4040 ElV
	Total/margin	1,783 with 43% margin. ELV launch capability margin 95% for Atlas 401, 56% for Delta IV 4040	No challenge, good mass margin
Thermal	—	Unknown	Unknown
Radio-frequency communications	Uplink	Unknown	Unknown
	Downlink	500 kbps	No challenge
Alignment	—	Unknown	Unknown
Propulsion	Delta-v	215 m/s, 172 kg propellant	No challenge

NOTE: Acronyms are defined in Appendix G.

EPIC-F Technical Margins The EPIC-F mission team provided a fairly complete description of its concept and showed good technical margins, although no margins were provided for attitude control and data communications. In addition, the sensitivity needed for the instrument is significantly greater than was required for previous instruments and will present a very significant technical challenge to meet.

EPIC-F Management Challenges The EPIC-F team is led by a principal investigator from the California Institute of Technology, with team members from JPL; the University of California, Berkeley; the Lawrence Berkeley National Laboratory (LBNL); the University of Chicago; the University of Colorado; the University of California, Davis; Cardiff University; and several other institutions. The EPIC-F project will be managed by JPL and is certainly within the experience base of missions led by JPL in the past. It was not possible for the committee to tell if there is a significant dependence on non-U.S. team members to be critical resources. A strong and experienced project manager will be needed to manage this large team.

No mission-level schedule was submitted by the EPIC-F team. Based on the phasing included in the cost estimate, the mission team has approximately a 60-month Phase B/C/D schedule. This schedule seems reasonable based on the complexity of the mission and the current TRL levels of the critical technologies.

The mission team claims to have extended Phase C/D to allow more time to develop the cryogenic instrument. According to the EPIC-F team, "The instrument schedule was developed in analogy with phase C/D plans for similar missions, WISE [Wide-field Infrared Survey Explorer] and Spitzer, and is longer than the planned phase C/D for either mission, but shorter than the actual phase C/D of Spitzer."[11] The development of the cryogenics payload will be the most significant schedule challenge for the mission, along with the integration of the payload with the commercial spacecraft bus.

EPIC-F Unique Challenges Liquid helium dewars have been used on previous spacecraft and should be reliable enough to meet the 2-year mission life expectancy but will remain a special challenge for EPIC.

According to responses provided by the EPIC-F team concerning risk management, "A demonstration of the EPIC instrument is now being developed for a balloon experiment named Spider, led by EPIC team members Lange, Bock, Golwala and Irwin, that incorporates 6 refracting telescopes with aperture-filling half wave plates, and focal planes of antenna-coupled TES bolometers. Spider will use a spinning observing strategy in a 20-day flight to demonstrate the essential operations planned for EPIC, although at reduced sensitivity and observation time."[12] This should be an excellent risk-reduction activity, especially with regard to the cryogenic instrument performance and operating time validation.

EPIC-I Mission

EPIC-I Technical Challenges: Instrument The Einstein Polarization Interferometer for Cosmology (EPIC-I) mission team is proposing corrugated horn antennas similar to those flown on the Cosmic Background Explorer (COBE). An ortho-mode transducer and Fizeau combiner are described very briefly, but there is not enough information to allow the committee to assess the TRL or DoD of the components or an integrated system. If the horns are nearly identical to those on COBE, the TRL would be above 6. The mission team has also identified alternate phase modulator technologies. The fact that phase modulator technology is listed as number 1 on its list of primary technical issues indicates that the TRL is significantly below the TRL 6 at which the team rated it. A technology readiness summary for the EPIC-I mission is presented in Table 3.16.

The detectors proposed are bolometers with cryogenics provided by a superfluid liquid helium cryostat and a single-shot ADR. As with the horns, the bolometers could be at high TRL if they are truly very close to the NTD Ge devices used for Planck and Herschel or to the TES devices from the Submillimeter Common User Bolometer Array (SCUBA) and the Green Bank Telescope (GBT). The actual "heritage" is not described. The most up-to-date

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[11] EPIC-F team response to Risk Questions from the committee, p. 2.
[12] EPIC-F team response to Risk Questions from the committee, p. 3.

TABLE 3.16 EPIC-I Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
Feed horns	COBE, WMAP	COBE flew corrugated horn antennas; WMAP devices below 100 GHz	Orthomode transducers for the required frequencies have been built, but little information is given.	9 (?) for antennas and "probably 6" for the phase modulators	Not enough information provided to assess	Not enough information provided to assess
Detectors	Planck, Herschel or SCUBA, GBT	Not provided	Proposing cooled bolometers; high Technology Readiness Level assumed due to past flight heritage, but little information provided.	8 or 6	Not enough information provided to assess	Not enough information provided to assess
Phase modulator	Ground-based BICEP and MBI instruments	Ferrite core	Alternative phase modulator technologies (i.e., MEMS switches or varactor-diode controlled nonlinear transmission lines) possible.	6 for ferrite core version	Not enough information provided to assess	Not enough information provided to assess
Cooling technology	Spitzer, ISO, Herschel, COBE, Suzaku	Not provided	Proposing a helium cryostat and a single-shot ADR. Not enough information provided to assess.	9	Not enough information provided to assess	Not enough information provided to assess

NOTE: Acronyms are defined in Appendix G.

RFI response references a ground-based testbed (main beam interference [MBI]) for testing EPIC-I technologies, but no details are provided.

If the cryogenic technologies (helium cryostat and ADR) are close clones of devices already flown their TRLs would be high, but insufficient information is provided. The fact that cryogenics is listed as number 2 on the mission team's list of primary technical issues indicates that the heritage may not be close enough for high-TRL/low-DoD ratings. While the information provided shows that EPIC-I has made significant progress in mission redesign, there is not enough engineering information provided to allow the committee to assess the technologies accurately.

EPIC-I Technical Challenges: Spacecraft EPIC-I plans to use a spacecraft that is similar structurally to the Coriolis, Swift, and GeoEye-1. The configuration is similar to the COBE configuration, with sunshields protecting the instrument, spinning, in a Sun-synchronous orbit. The avionics architecture and subsystems will be the same as for the Gamma-ray Large Area Space Telescope (GLAST) spacecraft with minor changes to match the EPIC-I requirements. All changes represent a reduction of requirements relative to GLAST. There are no significant spacecraft challenges for the EPIC-I mission. Spacecraft accommodation requirements for the EPIC-I mission are listed in Table 3.17.

EPIC-I Technical Challenges: Operations The EPIC-I mission team provided very little information concerning flight operations. The committee assumes that a cryogenically cooled spinning spacecraft will have the same balance issues and center of gravity issues similar to other missions of this type.

TABLE 3.17 EPIC-I Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	3 arcmin control, 1 arcmin knowledge, 1 RPM spin about the boresight	No challenge
	Tracking	None	Not applicable
	Jitter	Not stated	Unknown
Power	—	250 W payload with 25% contingency, 533 W total with 16.5% contingency, 24% margin	Six solar array surfaces on three wings. Sun synchronous orbit, adequate margin.
Data storage	—	0.5 GB	No challenge, 2 GB capacity
Structure	Payload	1,590 kg with 25% contingency	No challenge
	Bus	674 kg bus dry mass with 13% contingency	No challenge for the planned Atlas V 401.
	Total/margin	2,261 kg dry with 22% margin ELV launch capability margin 184% for Atlas 401	None, good mass margin
Thermal	—	Cold biased passive with heaters. Payload thermally isolated from bus	Minor challenge in the thermal isolation. Has been done before.
Radio frequency communications	Uplink	S band 2 kbps	No challenge
	Downlink	8 Mbps science, X-band 32 kbps housekeeping, S band	No challenge
Alignment	—	Spin balanced	No challenge
Propulsion	Delta-V	233 m/s, 324 kg propellant	No challenge for 2-yr lifetime capability is 283 m/s with 21% contingency.

NOTE: Acronyms are defined in Appendix G.

EPIC-I Technical Margins The EPIC-I concept appears to have adequate technical margins. Mass margin, in particular, is more than adequate at 184 percent, given the use of the Atlas 401 launch vehicle (under the assumption that the Delta II will not be available).

EPIC-I Management Challenges The EPIC-I team is led by a principal investigator from the University of Wisconsin-Madison. The team's industrial partner is General Dynamics, and team members include those from Cardiff University, the University of Richmond, and Brown University. Ball Aerospace is also involved in development of the instrument.

Inadequate information was provided to allow the committee to assess any schedule management challenges for EPIC-I.

EPIC-I Unique Challenges The use of a cryogenic dewar (and the associated thermal isolation requirements) is the major accommodation challenge faced by EPIC-I. This is within the state of the art, though, and is not a major driver for the mission.

TABLE 3.18 ADEPT Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Change from Previous Mission/Comments	Project Rating	Committee Rating	Committee Rating
Optics	NextView	Basic design	Uses 1.3 m telescope. 1.3-2.0 μm slitless spectrometer.	High	Not enough information provided to assess	Not enough information provided to assess
Detectors	Multiple	Basic design	Uses 2 μm 2k × 2k Hawaii HgCdTe detectors with 2 μm cutoff. Has to have the cutoff wavelength modified for ADEPT.	High	Not enough information provided to assess	Not enough information provided to assess
Optics	GeoEye I	Optical design	Uses 1.3 m, f/12 telescope, scaled up from GeoEye.	High	Not enough information provided to assess	Not enough information provided to assess
Spectrometer	Unknown	Unknown	Operates in the 1.3-2.0 micron, Hα range.	High	Not enough information provided to assess	Not enough information provided to assess

NOTE: Acronyms are defined in Appendix G.

Joint Dark Energy Missions

ADEPT Mission

The Advanced Dark Energy Physics Telescope (ADEPT) mission team did not provide detailed technical or programmatic information. The team citied concerns about proprietary information and competition sensitivity as its reason for doing so.

ADEPT Technical Challenges: Instrument It was stated by the ADEPT mission team that the mission will be based on technologies developed for missions such as Swift and GeoEye. Project documentation[13] states that "while there are differences, ADEPT has many similarities to the GeoEye-1 mission, which provides extensive heritage for ADEPT. In some areas ADEPT is somewhat simpler, and in some areas it is more complex, but comparisons are useful and warranted." The information provided was not sufficient for the committee to perform realistic assessments of TRL or DoD. From the general statements made, ADEPT appears similar in complexity to the other JDEM missions. The technology readiness of the ADEPT mission is summarized in Table 3.18.

The mission team states that it will be using a Hawaii HgCdTe 2k × 2k infrared detector sensor. The cutoff frequency will be modified for ADEPT to 2 μm. There is some challenge to this modification, but there are ongoing programs that should demonstrate even lower cutoff frequencies.

ADEPT Technical Challenges: Spacecraft Not enough information was provided to allow the committee to judge the challenges faced by the ADEPT spacecraft. Spacecraft accommodation requirements for ADEPT are shown in Table 3.19.

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[13] JDEM/ADEPT team response to the committee's Request for Information (see Appendix E in this report), January 2007.

TABLE 3.19 ADEPT Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	Not specified	Unknown
	Tracking	Not specified	Unknown
	Jitter	Not specified	Unknown
Power	Payload	Not specified	Unknown
	Bus	Not specified	Unknown
Data storage	—	Not specified	Unknown
Structure	Payload	695 kg	No challenge
	Bus	1,260 kg	No challenge
	Total/ margin	1,955 kg	No challenge
Thermal	—	Not specified	Unknown
Radio-frequency communications	Uplink	2 kbps command at S band	No challenge
	Downlink	8.5 Mbps	No challenge
Alignment	—	Not specified	Unknown
Propulsion	—	Not specified	Unknown

NOTE: Acronyms are defined in Appendix G.

ADEPT Technical Challenges: Operations ADEPT redshift survey operations involve agile reorientation of the telescope on a regular basis to acquire targets of opportunity. The Swift mission has the same requirement and has been able to meet the requirement without stressing the attitude control system (ACS). The ACS is not thruster-based and thus does not consume fuel in the process of reorienting the telescope. This design has a considerable design and mission-life advantage over conventional propellant-based technology. Although very little information was provided concerning flight operations, the operational aspects of ADEPT seem to be no more complicated than those of Swift.

ADEPT Technical Margins The mission team did not provide sufficient information concerning the spacecraft and mission concept to allow the committee to assess the technical margins of the ADEPT concept.

ADEPT Management Challenges No information was submitted that allowed the committee to assess the ADEPT team's organization or schedule management.

DESTINY Mission

DESTINY Technical Challenges: Instrument The only identified challenges in the Dark Energy Space Telescope (DESTINY) technologies are in the precision pointing and stabilization, identified by the mission team as challenges. The summary of the technology readiness of the DESTINY mission is shown in Table 3.20.

TABLE 3.20 DESTINY Technology Readiness

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
Three-mirror astigmatic telescope	IKONOS-1	Optical design and components	Scale size	7	7	N/A
1.65 m primary mirror	HST	Size of mirror	Slightly smaller than that on the HST	7	7	N/A
Spacecraft bus	Spitzer	3-axis bus carrying a large telescope	Different ELV, different thermal environment, vibration isolated reaction control wheels.	7	7	N/A
Detectors	HST JWST NIRSpec	Similar material and configuration	Different cutoff wavelength of the HgCdTe detector material	6	5	II

NOTE: N/A, not applicable. Acronyms are defined in Appendix G.

The optics required for DESTINY are within the state of the art for size, prescription, and precision. Employing a 1.65 m primary mirror with the required optical figure, the optics for DESTINY can be built without any special challenge.

The proposed detectors are 2k × 2k Hawaii-2RG devices. While the Single Channel Analyzers are very similar to devices on JWST, there are differences, most notably the cutoff wavelength. The new cutoff material has been demonstrated for the Hubble Space Telescope (HST) program, and this development will be leveraged in the DESTINY program. The DESTINY team is looking at investments required at Teledyne-Brown (the detector manufacturer) beyond those being made by JWST; the team noted that a prototype FPA was being developed. The information provided was not sufficient for the committee to judge the TRL to be 6. Substantial, ongoing investment efforts suggest that the DoD for the DESTINY application should be low (DoD = II).

Destiny Technical Challenges: Spacecraft The only challenge for the spacecraft is in the area of pointing and stabilization, and it depends in large part on the performance of the camera fine-guidance subsystem. There was not enough information provided to the committee for judging the merit of the fine-guidance subsystem. Spacecraft requirements generated by the DESTINY science payload are listed in Table 3.21.

DESTINY Technical Challenges: Operations Based on a 1.65 m telescope operating at L2, DESTINY will survey 1,000 square degrees of the sky in the near-infrared (NIR), performing a weak-lensing survey of candidate supernova (SN) Ia objects. The detectors are passively cooled, and the spacecraft is not spinning. Attitude control uses reaction wheels and not thrusters, thus eliminating the operational challenge of managing consumables. The mission appears to have good heritage, and from what was presented to the committee, it should be simple to operate.

DESTINY Technical Margins The DESTINY mission concept proposed had adequate technical margins for size, weight, power, and other performance parameters, with the exception of pointing stability and control, where it is unclear whether the proposed concept will perform adequately. Specifically, there are concerns with jitter from propellant slosh and other systematics that could present a problem for pointing repeatability. To prove out the proposed pointing and control concept, additional analysis will need to be completed to provide a more thorough understanding of these issues.

DESTINY Management Challenges The DESTINY mission is led by a principal investigator from the National Optical Astronomy Observatory and the NASA GSFC. Team members are based at the Space Telescope Science

TABLE 3.21 DESTINY Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	3×10^{-6} deg	Handled by camera fine pointing subsystem. Uses image differencing for fine pointing.
	Tracking	Not specified	Unknown
	Jitter	3×10^{-9} deg/s	Uses rates from IMU but controlled by camera fine point system.
Power	Obital average	785 W (with 30% contingency) for the payload, 451.6 W (with 30% contingency) for spacecraft bus	Drives array size but is not a challenge.
	Worst case	988.4 W (with 30% contingency) for spacecraft bus	Drives array size but is not a challenge.
Data storage	—	62.5 GB	Cost
Structure	Payload	1,784 kg (with 30% contingency) for payload, 1,798-2,059 kg for spacecraft bus. 9-28% mass margin above contingency depending on which bus design is used	No particular impact or challenge, although discipline will have to be followed in managing mass.
Thermal	—	Allocated 104 W for operational heater control	No challenge
Radio frequency communications	Uplink	2 kbps	No challenge
	Downlink	28 Mbps at Ka band for science downlink	No challenge
Alignment	—	Not specified	Unknown
Propulsion	—	150 m/s, 182 kg propellant	No challenge

NOTE: Acronyms are defined in Appendix G.

Institute; Harvard University; Texas A&M University; the University of California, Davis; Michigan State University; the University of Chicago; and the Carnegie Observatories.

Assuming that the current team responsibilities remain the same, there are no obvious management challenges to the DESTINY mission. There is no significant dependence on non-U.S. team members for contributions of funding or equipment. The size of the team is not particularly large and should be manageable with established management processes.

The mission team provided very little schedule information. It states that only 5 years are required from start to launch readiness, but there is no support for this claim. Since there is very little in the way of new technology, this claim of 5 years for development is possible.

DESTINY Unique Challenges The only special challenge discussed by the DESTINY team is the risk associated with pointing repeatable to 0.05 pixels or 0.01 arcsec. Pointing at this accuracy is handled by the fine-guidance system but is a design driver.

SNAP Mission

SNAP Technical Challenges: Instrument SNAP key technologies are either mature (TRL 6 or greater) or progressing toward TRL 6 in well-planned steps. A technology readiness summary of the SNAP mission is shown in Table 3.22.

TABLE 3.22 SNAP Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comment	Project Rating	Committee Rating	Committee Rating
Telescope	HST, Classified IKONOS	Components, design	Uses an annular field, Korsch type 1.8 m, f/12 lightweight telescope with three-mirror anastigmatic design. Uses Zerodur or ULE composite mirrors and composite metering for low CTE properties.	9	>6	N/A
Si Sensor	HST/ WFC3	Manufacturing processes	CCDs are innovative n-type high-resistivity devices produced by LNBL; they have undergone extensive testing to demonstrate that they exceed specifications.	6	6	N/A
Si CCD electronics	NeXT, Bepi-Colombo	Manufacturing processes	Two ASICs are required and one has been demonstrated. The most recent SNAP inputs indicate that the other (the clocking chip, or CLIC) is currently undergoing testing. No integrated demonstration has been performed.	5	4-5	I-II
MCT sensor	JWST, WFC3	Commercial product. Same device as JWST	Uses 36 Raytheon- or Rockwell-supplied 1,700 nm cutoff HgCdTe for IR.	6	6	N/A
MCT electronics	JWST	Based on SIDECAR's ASIC	Will be used without modification for SNAP.	6	6	N/A
Focal plane plate	JWST/ NIRSpec Spitzer	Optical layout, materials	Requires $\lambda/\delta\lambda = 70$-100 resolving power over the 0.4 to 1.7 micron band-pass to measure the SiII line to +400 km/s. Prism-based design.	6	4-5	II
Spectrographic image slicer	JWST	Design	Innovative design developed for the JWST NIRCAM instrument. Literature cites prototype testing in a relevant environment but gives no detail.	5	5	I-II
Spacecraft structure and other components	Spitzer, other	Standard structure and subsystems	Requires no new technology or development—standard components with flight heritage.	9	>6	N/A
Ka-band transmitter	None	Components	Transmitter will be assembled from flight-proven components, but no integrated demonstration indicated.	7	4-5	I-II

NOTE: N/A, not applicable; SIDECAR, system image, digitizing, enhancing, controlling, and retrieving. Other acronyms are defined in Appendix G.

SNAP plans to use a 1.8 m composite telescope. The telescope will have a large FOV and is designed with care for thermal and optical performance. The weak-lensing experiment is highly dependent on the optical performance of the telescope. The telescope development is seen as a straightforward engineering effort with no obvious challenges (TRL = 7) and is within the experience gained on multiple other programs.

SNAP uses two types of detectors: an LBNL-supplied, radiation-hardened CCD and a Rockwell- or Raytheon-supplied mercury cadmium telluride (MCT) IR detector. The Department of Energy (DOE) has made significant investments in detector development (both Si CCD and HgCdTe [MCT]). The MCT cutoff of 1.7 microns is below space-proven technology, but development efforts have been highly successful. The JWST and HST Wide Field Camera 3 programs are developing the manufacturing base that they will need to ensure availability. The CCDs are a custom item developed by LBNL for the Department of Defense (DOD). The performance of the CCD meets requirements, and relevant testing has been done on flight-like parts. The ability of LBNL to produce the required number of CCDs in the needed time frame is a concern, and LBNL's latest literature indicates that it is transferring processing technology to DALSA Semiconductor for routine processing. The development of the ASICs (two needed) for the CCDs is progressing. A prototype of the clocking chip has been manufactured and was to start testing in April 2007. The ADC has been produced and tested. The committee rated the CCD electronics at a TRL of 4-5 because the testing of the prototype and integrated testing had not been performed; there should be no extraordinary challenges, however, and the DoD should be low (I-II). MCT detectors with the required cutoff and quantum efficiency (QE) have been demonstrated under DOE funding, although little discussion of the testing (e.g., length) is provided. The required ASIC has been developed for JWST, so the MCT should be at the claimed rating of 6 (assuming that the material testing was comprehensive and of the required fidelity). Assuming that funding can be provided in the needed time frame, these devices should not be a challenge. It should be noted that fully integrated demonstrations of the sensors systems have not been completed. The readout electronics for both detectors are claimed to be radiation-hard and with adequate performance to meet mission objectives. The performance of the integrated instrument could be a challenge to maintain low noise levels over temperature.

The planned focal plane plate will be "roughly twice as large as prior cryogenic flight focal planes in terms of pixel complement"[14] and will require development efforts. Therefore, the committee rated it at a TRL of 4-5 rather than the 6 given by the mission team. It appears that the mission team has researched the development effort and that the materials and engineering processes should be available for the development effort, so the committee rated the DoD at II. All components in the spectrograph are standard and should pose no development risk with the exception of the Image Slicer (IS). There is heritage from JWST (Near-Infrared Camera), but very little detail was provided on the prototype or testing (e.g., how close is the prototype to the SNAP design and what specific testing has it undergone?). If the prototype is a very close match and the testing was high fidelity with respect to SNAP requirements, then the TRL should be 6. The discussion (on page 31) in the mission team's response to the committee's RFI (IS TRL = 6) is not consistent with the rating (TRL = 5) provided in Table 9 on the same page of the response, and not enough information is provided to make the distinction. If the IS is at TRL 5, the DoD should not be high (DoD = I to II) based on its similarity to that on JWST.

Finally, the Ka-band transmitter calls for the use of all flight-proven parts. Similar transmitters have flown but not with the required wideband mixer. Wideband mixers have flown but not for the same application. In this case, components have been widely demonstrated, and other programs (the Solar Dynamics Observatory and the Lunar Reconnaissance Orbiter) will fly similar hardware (few details on the latter were provided). The development and testing of an integrated unit were not described, so the TRL is judged to be between 4 and 5. The engineering should be straightforward, and the DoD is judged to be low (I-II). The Ka-band resource availability of the Deep Space Network could be a problem for SNAP.

SNAP Technical Challenges: Spacecraft Only in the areas of ACS performance and downlink data rates might there may be some challenges with the spacecraft. Spacecraft accommodation requirements for the SNAP mission are shown in Table 3.23.

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[14] SNAP team response to the committee's Request for Information (see Appendix E in this report), January 2007.

TABLE 3.23 SNAP Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	3 arcsec	No challenge
	Tracking	6 deg/min	No challenge
	Jitter	0.02 arcsec/1,000 s	Complexity
Power	Payload	270 W/30% contingency	No challenge
	Bus/total	343 bus/613 W total with 30% contingency	No challenge
Data storage	—	137.5 GB	Cost
Structure	Payload	985 kg/30% contingency	No challenge
	Bus	493 kg dry with 25% contingency	No challenge
	Total/margin	1,571 kg with 28.3% contingency. 747 kg total LV mass margin	No challenge
Thermal	—	Adiabatic interface between spacecraft and instrument—negotiated maximum allowable heat transfer from spacecraft to instrument	Unknown
Radio-frequency communications	Uplink	2 kbps	No challenge
	Downlink	150 Mbps with 50% contingency	Unknown
Alignment	Telescope	Active alignment system	Complexity, reliability
Propulsion	—	93 kg propellant	No challenge

NOTE: Acronyms are defined in Appendix G.

SNAP Technical Challenges: Operations SNAP is a very well developed mission requiring only passive cooling for its detectors, fixed solar array, and an achievable pointing accuracy performance. SNAP will perform a weak-lensing sky survey over about 1,000 square degrees in a time frame of about 1 year. The mission performance requirements are exceptionally well developed. SNAP presents no special operational issues. Observing targets will be selected and command sets uploaded periodically to schedule pointing and observing time for specific targets.

SNAP Technical Margins The SNAP mission team provided significant detail on its proposed concept and showed adequate technical margins in all areas.

SNAP Management Challenges The SNAP mission will be co-led by principal investigators from the LBNL and includes members from the University of California, Berkeley; LBNL; the California Institute of Technology; Fermi National Laboratory; the University of Maryland; the University of Michigan; the University of Pennsylvania; Laboratoire d'Astrophysique de Marseille (France); Institut National de Physique Nucléaire et de Physique des Particules (France); and several other institutions. The project will be managed by the University of California, Berkeley. Managing the SNAP project that has international partners providing key spectrometer hardware could prove to be a challenge.

The proposed schedule shows 4.75 years from the PDR to launch. This is barely adequate development time for a mission of this complexity. The committee could not tell from the materials provided how much reserve was included in the schedule. Schedule management should not be a challenge unless problems develop with the instrument. The spacecraft should not be a problem, although ACS performance is quite demanding.

LISA Mission

LISA Technical Challenges: Instrument The optical materials, components, and techniques used in LISA have significant heritage, and the LISA Pathfinder (LP) optical system (while different in design) will provide significant confidence in the system.[15] The LP engineering model (EM) has already undergone extensive testing. Development of the optical system appears to be a straightforward engineering effort with a very high probability of success. The LISA Pathfinder is on track to launch in late 2009, with 70 percent of the hardware to be delivered in 2007. The assessed TRL and DoD levels for the key technologies to be demonstrated by the LISA Pathfinder are shown in Table 3.24, which contains a summary of LISA technology readiness issues.[16]

The phase measurement system (PMS) for LISA employs both a photo receiver and a phase meter. Other missions have used architectures similar to the one planned for LISA, and ongoing breadboard testing of both components has been successful to date. An integrated prototype development effort is planned, and the current schedule indicates that TRL 5 and 6 for the integrated system will be attained in 2009 and 2010, respectively (assuming success). While the current TRL is low, an adequately funded development effort should be relatively straightforward (DoD = II).

The micronewton thrusters are the most challenging technology being developed by the LISA team. Three different thruster types are being evaluated for LISA: (1) Colloid Micronewton Thrusters (CMTs), (2) Indium Needle Field Emission Electric Propulsion (In-FEEP) devices, and (3) Cesium Field Emission Electric Propulsion (Cs-FEEP) devices. While all of these have demonstrated the performance characteristics (thrust level and low noise) required for the LISA mission, none has demonstrated the very taxing lifetime requirement stated in LISA documentation (>50,000 hours). In the United States, a CMT design has been developed and will fly as part of the LISA Pathfinder mission. In the course of its development, multiple 3,000 hour endurance tests were performed, and three life-limiting issues were identified and resulted in design changes. In Europe, designs of both FEEP thrusters are being tested, and one will be chosen for demonstration on LISA Pathfinder. While various FEEP components and/or systems have accumulated thousands of hours of testing, program documentation indicates that the longest end-to-end testing is less than 10 percent of the required lifetime. The micronewton thrusters must work for LISA to be successful. The lack of endurance testing, the inability to perform qualification-level testing prior to the 2009 time frame (from a time perspective), and the problems encountered to date indicate that this is a significant risk area with a high degree of difficulty. While the mission team is working on three alternatives, adding alternate implementations (e.g., the addition of more thrusters to mitigate life requirements) to its planning would enhance the mission's viability.

Three separate techniques are being considered for laser frequency noise suppression. These are (1) laser prestabilization (PS), (2) arm locking (AL), and (3) time delayed interferometry (TDI). All three have promise: PS demonstrations have exceeded LISA requirements in laboratory demonstrations, AL is routinely used in ground-based systems, and computer simulations have shown that TDI should work. The documentation provided does not indicate the fidelity of the demonstrations with respect to LISA. Both AL and TDI system-level testing is ongoing, but again, the relation of these tests to LISA is not explained. While it is not expected that the ultimate development will have a high DoD (estimated at DoD = II), the TRL is 3-4.

LISA Technical Challenges: Spacecraft The LISA spacecraft has been described as a "science craft," as the spacecraft bus is built up around the interferometer. Table 3.25 lists the LISA spacecraft accommodation requirements and issues.

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[15] The LISA optical components are documented in multiple documents: Gaussian Optics Design Rules (LISA-ASD-3001), Opto-Mechanical Payload Design (LISA-ASD-TN-3002), Telescope Design and Tradeoffs (LISA-ASD-TN-3003), and Optical Analysis and Beam Warrior (LISA-ASD-TN-3004).

[16] The committee treated LISA as an integrated NASA-ESA project and thus did not distinguish between NASA and ESA technologies.

TABLE 3.24 LISA Technology Readiness Summary

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comments	Project Rating	Committee Rating	Committee Rating
Gravitational reference sensor	GRACE	Common design features, but has a weaker coupling to the spacecraft. LISA system requirements are more demanding than those of GRACE.	EM being built for LISA Pathfinder. Currently at CDR level. Extensive laboratory testing of EM to date.	4	4	III-IV
Micronewton thrusters	LISA Pathfinder	Will fly two types of thrusters on Pathfinder. Extensive laboratory testing of units for periods typically less than 15% of required lifetimes.	ST-7 will demonstrate functionality but not life.	4-5	3-4	IV
Optical assembly pointing mechanism	None stated	Project claims that multiple commercial mechanisms are meeting requirements, but the project is also working on an alternate to the baseline pointing architecture and concepts for new mechanisms.	Not enough information provided to judge—if commercial units are to be used, then TRL is likely high, but if a new architecture employing a new concept is selected, then the TRL is reduced.	6	4-5	II
Point ahead actuator	None stated	Not applicable	This is a critical component with tight operational tolerances (e.g., no motion at the picometer level); ESA has a planned development program with breadboard-level testing.	3	3	II-III
DRS control laws	GPB; LISA Pathfinder	LISA Pathfinder will demonstrate functionality.	Simulations have demonstrated that DRS controls can be implemented for LISA, and LISA Pathfinder will demonstrate the required technology.	6	5	II-III
Laser system	TerraSAR; NFIRE	Laser will fly on TerraSAR, and the system is to fly as a secondary payload on NFIRE.	The EM master laser developed for LISA Pathfinder puts this component at TRL 6. A space-qualified fiber amplifer with a broadband electro-optic modulator is currently being tested. An end-to-end EM system is under development, and a qualification program is in place to bring the system to TRL 6 in 2010.	4-6	4	II-III

continued

TABLE 3.24 Continued

	Heritage			TRL		DoD
Element	Mission	Similarities	Changes from Previous Mission/Comments	Project Rating	Committee Rating	Committee Rating
Laser frequency noise suppression	None claimed	Not applicable	Three techniques (pre-stabilization [PS], arm locking, and time delayed interferometry) are discussed. PS exceeding LISA requirements has been demonstrated, AL is stated to be a standard technique for ground-based interferometry, and TDI computer simulations indicate that the technique should work. Systems-level tests are in progress.	4	3-4	II
Phase Measurement System (PMS)	GRACE; (Blackjack GPS receiver); LISA Pathfinder	Baseline architecture similar to GPS and GRACE.	Breadboard component testing is promising so far. System verification is planned for increasing TRL to 5 by 2009 and 6 by 2010. The LISA Pathfinder system is different from the LISA system, but the demonstration will be highly relevant.	3	3	II
Optical system	LISA Pathfinder	LISA Pathfinder will qualify components.	System design is well advanced and employs well-developed components. The LP system is similar to the LISA system; the LP EM unit has undergone extensive, successful testing.	5-6	5	II

NOTE: Acronyms are defined in Appendix G.

LISA Technical Challenges: Operations The three LISA spacecraft will be separated by 5 million kilometers in flight. In order to begin operations as a space-based interferometer, the three spacecraft will have to find each other and orient their lasers correctly. Maintaining signal to noise over this arm length and being able to extract phase information from signals with such low amplitude will be extremely challenging. Maintaining the proof mass in the right position will also be challenging. Noise sources ranging from solar pressure, solar wind buffeting, Earth-Moon gravity, and numerous interfering sources could also challenge the LISA measurement. While the operations of LISA have been very carefully considered and advanced plans are thorough and reasonable, this type of space operation has never been done before.

LISA Technical Margins The LISA project has completed numerous detailed engineering studies to back up the design and had adequate technical margins in all areas, except with the micronewton thruster performance and lifetime.

The micro-Newton thrusters required for the LISA program have not demonstrated an adequate lifetime to show margin. The requirement is for 55,000 hours of operation to meet the LISA mission life.[17] However, the

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[17] LISA team response to the committee's Request for Information (see Appendix E in this report).

TABLE 3.25 LISA Spacecraft Accommodation Requirements

System	Subsystem	Performance Requirements	Impact
Attitude determination and control	Pointing	Not specified for ACS, precision pointing handled by Disturbance Reduction System (DRS)	Significant for the DRS. Spacecraft bus requirements are stated to be achievable with conventional technologies.
	Tracking	Not specified for ACS, precision pointing handled by DRS	
	Jitter	Not specified	
Power	Orbital average	253 W (payload) 381 W spacecraft bus	Drives array area but can be met with standard GaAs cell technology.
	Worst case	766 W, 30% contingency	No challenge
Data storage	—	Approximately 32 MB	No challenge
Structure	Bus	314 kg	Only leaves 271 kg total mass margin on Atlas V 531.
	Payload	259 kg	
	Prop module	259 kg	
	Dry mass/space	832 kg	
	Propellant	474 kg	
	Wet mass/space	1,556 kg	
	LV adapter	200 kg	
	Total	4,868 kg for 3/wet spacecraft	
Thermal	—	10^{-3} K/Hz$^{1/2}$ at 1 mHz thermal noise	Unknown
Radio-frequency communications	Downlink	90 kbps at Ka band	No challenge
	Uplink	2 kbps at Ka band	No challenge
Alignment	—	1 mrad telescope to optical bench	No challenge
Propulsion	—	1,169 m/s, 474 kg propellant	Size, complexity, mass.

NOTE: Acronyms are defined in Appendix G.

currently demonstrated lifetime is on the order of 8,000 hours. While the LISA team has identified risk-mitigation plans, including maintaining multiple suppliers, ground tests, and flight tests on the LISA Pathfinder, it remains a significant issue for the success of the mission that will require time to resolve. In addition, thermal control of the thermal noise is likely to be troublesome and could drive resources.

LISA Management Challenges LISA is a joint NASA-European Space Agency (ESA) project, based on a September 2001 Letter of Agreement and an August 2004 Formulation Phase Agreement between the two agencies. A Joint Project Management Office for LISA was established in 2001, with NASA and ESA project managers and project scientists, who work in close collaboration. In addition, there are integrated technical and engineering teams working jointly on such technologies as the disturbance reduction system and the interferometry measurement system. Although ESA is the lead agency in developing Pathfinder there is significant NASA participation (under the NASA designation ST-7). There is considerable overlap between the technical and engineering teams building Pathfinder and those working on LISA. The project presented a well-organized team with good depth in each technical discipline.

The LISA mission is planned to be co-funded by NASA and ESA and is thus dependent on each partner to maintain its contribution level and annual profile through the life of the project. As estimated by the project, the expected magnitude of the ESA contribution is approximately $440 million, in addition to funding the LISA Pathfinder mission, so ESA's participation is vital. For the LISA mission itself, ESA supplies the propulsion module that puts each spacecraft into its proper orbit, candidate micro-thrusters, and parts of the interferometry system. Managing the partnership between ESA and NASA is a major challenge, especially under the constraints imposed by high visibility and International Traffic in Arms Regulation (ITAR).

Leading to a launch in the first quarter of 2016, as shown in the LISA team's schedule, the LISA mission's critical path appears to be through the development of the micronewton thrusters and the phase measurement systems. The thruster's performance should be confirmed by the second quarter of 2010, which is in advance of the mission's PDR by about 9 months. If there are serious performance issues with the thrusters, 9 months is not adequate time to recover and requalify in time to hold the mission's launch date. Slipping schedule could cost about $1 million per month, according to the spending plan provided to the committee.[18] This seems underestimated, but the last 4 years before launch are about this same rate of spending.

LISA Unique Challenges The LISA mission is a very difficult mission to implement, and to succeed it will depend on all of the technology development activities going on during pre-Phase A and the LISA Pathfinder mission. The ability to operate a space-based interferometer involving three spacecraft for 5 years with an arm length of millions of kilometers is a daunting technical challenge in such areas as attitude control, phase measurement, laser performance, and flight operations. The mission team's suggested mitigations are (1) reduce the arm lengths and (2) reduce the mission lifetime. The first suggestion appears to be a descoping option to reduce performance risk with no associated cost savings, while the second is a descoping option to reduce cost. The reduction of lifetime could save approximately $25 million to $28 million per year. This is a challenge for LISA owing to the fact that it takes all three sciencecraft to perform the mission, and there is essentially nothing to descope during development as there is with a multisensor, multi-instrument mission. If LISA experiences significant cost problems in Phase C, there is little by way of descoping options to help, and NASA will face the decision of absorbing the overrun or canceling the mission. A post-Pathfinder mission review and recosting seems the best way to ensure that the operational flight system can be built to meet science performance requirements within cost and schedule.

MISSION COST ASSESSMENTS

Overview

In response to an expected NASA "funding wedge" that is to open in fiscal year (FY) 2009, NASA and DOE requested that the National Research Council (NRC) assess the Beyond Einstein mission areas and recommend one for first launch and development. To ensure cost realism, the NRC's Space Studies Board and Board on Physics and Astronomy, in consultation with NASA and DOE, identified the need for independent cost and schedule realism assessments for the 11 Beyond Einstein mission concepts. The purpose of the these assessments was to understand the projects' cost estimates using a consistent methodology based on previous missions of similar scope and complexity. The committee's goal was to provide a realistic expectation of the cost range for each mission.

Assessment Process, Criteria, and Considerations

The methodology employed to assess cost realism is as follows:

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[18] LISA team response to the committee's Request for Information (see Appendix E in this report).

1. Acquire and normalize data for the individual mission concepts.
2. Perform independent estimates of probable costs and development time to undertake the individual mission concepts.
3. Compare individual estimates with a complexity-based model to aggregate individual mission concepts into a range of cost for the Beyond Einstein mission areas.
4. Develop a budget profile for the committee's recommended mission sequence and compare it with the expected funding wedge to assess affordability and mission-ordering options.

Data Acquisition and Normalization

The first step in the process was to gather mission, instrument, technology, and spacecraft design data for each of the concepts to be considered, so as to have a common basis for assessment. Commonality was particularly important in this case, as there were broad variations in the level of detail and fidelity available or in what the advocates were willing to share. Some concepts were relatively mature, while others were closer to a conceptual paper. The committee sought to normalize these concepts to the extent possible to set a common ground rules and characteristics for comparison. The basic information required for estimating probable cost and cost ranges for each mission area was acquired by requesting information from the individual mission concept advocates through a Request for Information (RFI) process (see Appendix E in this report). The mission teams provided the committee with responses to the RFI and other public documents, presentation material from various public engagements and workshops, and other material describing the proposed mission concepts. In cases where restrictions on the distribution of the RFI data applied, the committee did not make use of the RFI responses. Spacecraft, instrument, and technology data for each of the concepts were gathered at the highest level of definition consistent with being able to have a common basis for relative assessments of cost and schedule. An implicit assumption is that the proposed concepts are feasible. As the Beyond Einstein mission concepts are at significantly different levels of definition, technology readiness, and development, the independent estimates involved normalizing these disparities to provide a common basis of comparison. In select cases the scarcity of data precluded an in-depth assessment of a specific mission. However, in all cases for the Beyond Einstein Probes there was sufficient information to assess more than one mission concept for each of the mission areas. An influential variable in the probable cost estimation methodology is the heritage/percent new design and TRL. TRL was assessed using the risk rating approach described in the previous section.

Estimation of Cost and Development Time

The methods and tools employed in the estimation of cost and development time were appropriate for conceptual-level assessments. Several parametric estimating tools and empirical databases of technical and programmatic information were used to independently estimate probable costs and schedule for the 11 mission concepts. QuickCost, a model developed by the Science Applications International Corporation (SAIC) for NASA, was the principal tool in this study.[19] QuickCost only requires objective information at the top level. This tends to level the playing field by obviating the need for the missions that are less well defined to provide information that is not yet mature. QuickCost was cross-checked with the NASA Air Force Cost Model (NAFCOM), another NASA cost model in common use in the aerospace sector.

Probable cost estimates are in terms of NASA "full costs," including an allowance for NASA (or DOE) civil service labor cost, contractor fee, and other institutional costs such as center management and operations, general and administrative, and overhead. Parametric models were calibrated to a set of past missions suggested by the committee as specific analogies described in the previous section. For each mission, the instrument and spacecraft bus TRLs were assessed (using the standard NASA TRL ratings), as well as the technology development degree of difficulty, and were translated into cost factors. Probable cost estimates were developed for each mission candidate.[20] In doing so, cost models were used to develop the cost estimates for preliminary design (Phase B), through full-scale development and production (Phase C/D). Comparisons to costs for similar missions were used to develop estimates of the cost for conceptual design (Phase A) and mission operations and data analysis (Phase E). Launch cost is a point estimate associated with the use of an evolved expendable launch vehicle (EELV) heavy or EELV medium, as dictated by the mission's launch mass and orbit destination.

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[19] SAIC, under contract to the NRC, provided the committee with cost-estimating expertise and tools to assist in the assessment of probable cost ranges for the candidate Beyond Einstein missions.

Comparison of Cost and Schedule Estimates with Historical Data

A critical question assessed by the committee is the question of when performance requirements reach a threshold at which they are no longer achievable within the allocated resources. To address this issue, the Complexity-Based Risk Assessment (CoBRA) model, developed by the Aerospace Corporation, was used as an independent cross-check on the project estimates and parametric model results. The goal is to understand how technical and programmatic complexity relates to cost and schedule at the system level. The complexity index is derived on the basis of performance, mass, power, destination, and technology choices, to arrive at a broad representation of the system for purposes of comparison.

In examining previously built systems, cost data are generally not publicly available at the subsystem level; therefore, a system-level assessment is desirable and appropriate. CoBRA integrates a broad array of technical parameters through a ranking algorithm to derive a complexity index for a given mission compared against an empirical database of missions previously flown or in development. The complexity indices are plotted versus cost and schedule to show overall trends and a range of cost and schedule. The mission team estimates (as available) and the independent parametric estimates of probable cost and schedule were overlaid against prior mission actual cost and schedule to assess the adequacy of resources and associated risk relative to missions of similar complexity. Using an aggregation of the various sources of estimates, a range of costs for each of the mission areas was defined.

Development of Funding Profiles

Using the ranges of cost and schedule for each mission area, funding profiles were developed for each mission. The funding profiles were assessed relative to available or projected budgets of NASA, DOE, and other sponsors (i.e., non-NASA/DOE partners) to determine the affordability of different scenarios. Two cases involve substantial potential contributions from agencies outside of NASA: LISA (ESA contribution estimated at $500 million[21]) and JDEM (DOE contribution estimated at $400 million[22]). It was assumed that the DOE JDEM contribution would apply to SNAP, ADEPT, DESTINY, or any other JDEM mission that NASA and DOE elected to move forward with. It was also assumed that Phase A and B are covered by the FY 2007 to FY 2009/FY 2010 Beyond Einstein funding wedge. For the budget comparisons, life-cycle cost (LCC) at 70 percent confidence was used (including design, development, test, and evaluation [DDT&E]; production; launch; and mission operations and data analysis [MO&DA]).

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[20] Both QuickCost and NAFCOM generate cumulative probability-density functions for cost such that a confidence level (percentile) may be chosen. To align with recent NASA policy, 70th percentile costs are reported here.

[21] According to the March 14, 2007, note from Thomas Prince, California Institute of Technology, to the committee, entitled "Summary of LISA Status in ESA Cosmic Vision": Given the high priority of LISA to the ESA program (as emphasized in the [Science Program Committee] recommendation), given the significant investment in LISA Pathfinder (which will launch in late 2009), and given that LISA has been in the formulation phase since 2005, it is widely viewed that LISA will be chosen to go forward into the definition phase. It will be the only Cosmic Vision program mission to have gone through a full formulation phase at the time of the decision about proceeding into the definition phase. It should also be noted that as a Cosmic Vision program mission, the investment by ESA in LISA can be increased from the current 340 million euro to 650 million euro.

[22] Kathy Turner, Office of High Energy Physics, Department of Energy, "Note to BEPAC Regarding DOE's JDEM Plans," March 30, 2007, e-mail communication: "Within the Office of High Energy Physics (OHEP), the out-year plan for the research portion of the budget will continue to support the dark energy program and is where the funds for JDEM would be provided. For out-year planning purposes, we have been using a DOE contribution to the total project cost of approximately $400 million. The FY 2007 budget and the President's Budget Request for FY 2008 have allocated resources for continuing our dark energy program, including funding for SNAP R&D. In addition, funding for FY 2007 in the amount of approximately $3 million and requested funding for FY 2008 of approximately $6 million will provide competitively selected R&D funding for both midterm and longer-term ground- and/or space-based dark energy concepts."

Results

Mission Concept Cost Estimates

Table 3.26 provides a summary of the independent cost estimates for the 11 Beyond Einstein mission concepts assessed by the committee. All of the costs are in real-year dollars except where noted otherwise.[23] DDT&E plus production (Phase C/D) is given in the first row. Launch services are assumed to be either $200 million for an EELV medium or $300 million for an EELV heavy. These two rows total to the mission acquisition cost. MO&DA is combined with acquisition cost to give the LCC (Phase C/D/E). For reference, the LCC as it was estimated by the advocates for each project is provided. Other metrics of interest are Phase B/C/D costs and schedule, which in this case are converted to FY 2007 dollars to allow direct comparison with the CoBRA plots. In all cases, the independent estimates were substantially higher than the project estimates. The range of cost results is shown in Figure 3.1; however, for purposes of the comparative and budget analysis that follows, the committee uses 70th percentile estimates in accordance with recent NASA policy.

Comparison with Historical Data

To understand how technical implementation relates to budget, a complexity index was derived, based on performance, mass, power, and technology choices. Data were assembled for a majority of robotic space missions launched over the past nearly two decades (1989 to 2007). The basis for the relationships is a database of technical specifications, costs, development time, mass properties, and operational status for more than 120 robotic space missions that fall into three general categories: (1) NASA planetary and near-Earth spacecraft, (2) NASA Earth-orbiting satellites, and (3) other U.S. government, non-NASA satellite missions serving as a baseline for comparison. Only robotic spacecraft missions that meet certain criteria and constraints were considered. Large (e.g., Hubble/Cassini-class), medium (e.g., Spitzer/New Frontiers-class), and small missions (e.g., Kepler/Discovery-class or smaller) were included. Missions that are nearing launch or have been launched but have yet to complete a significant portion of their science missions are included, but it is noted that success has yet to be determined. No human-rated systems or launch systems were considered.

The complexity index uses a matrix of technical factors to place in rank order a new system relative to a baseline data set. Complexity drivers include more than 30 objective technical parameters (mass, power, performance, design life, pointing accuracy/control, downlink data rate, technology choices, propulsion, mechanisms, software/data management, and so on). All parameters are demonstrable parameters dictated by project, mission, or system requirements. In this case, the "development" costs and schedule (Phases B/C/D) were considered excluding launch and MO&DA (Phase E). The total flight system development costs (payload instruments and spacecraft bus, excluding launch and operations) and development times (period of time from contract start until ready for launch) are the independent variables against which complexity is compared. From the information in Table 3.26, total development costs (Phase B/C/D) were derived in current-year dollars (millions of FY 2007 dollars).

The resultant comparison of the Beyond Einstein missions against the empirical data set is shown in Figures 3.2 and 3.3. The first thing to note is general agreement between the independent probable cost estimates and the historical actuals (cost and schedule). Note also that "in-development" (not yet launched) missions are shown for purposes of comparison; however, the regression curves are derived from the "successful" missions (launched and met or having exceeded science goals). There are four "bins" of complexity beginning with JDEM on the low

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[23] Inflation is taken into account using the standard NASA inflation index.

TABLE 3.26 Summary of Committee Cost Estimate Results (in millions of real-year dollars, except where noted)

	Joint Dark Energy Mission			Black Hole Finder Probe		Inflation Probe				Einstein Great Observatories	
	DESTINY	ADEPT	SNAP	CASTER	EXIST	CIP	CMBPol	EPIC-F	EPIC-I	LISA	Con-X
DDT&E + production (excluding Phase A/B) at 70% confidence	$1,132[a]	$973	$1,116	$1,588	$1,290	$876	$910	$980	$1,030	$2,318	$2,059
Launch services	$200	$200	$200	$300	$300	$200	$200	$200	$200	$300	$300
Partnering credits (DOE for JDEM; ESA for LISA)	($400)	($400)	($400)	$0	$0	$0	$0	$0	$0	($500)	$0
Acquisition subtotal	$932	$773	$916	$1,888	$1,590	$1,076	$1,110	$1,180	$1,230	$2,118	$2,359
MO&DA	$198	$293	$410	$584	$389	$260	$103	$111	$57	$641	$695
Life cycle cost at 70% confidence	$1,130[a]	$1,066	$1,326	$2,472	$1,978	$1,336	$1,213	$1,290	$1,287	$2,759	$3.054
Mission team estimated life cycle cost—for reference	*$834*	*<$1,000*[b]	*$724*	*$993*	*$1,095*	*$683*	*$700?*	*$800*	*?*	*$2,045*	*$2,162*
Estimated Phase C/D duration (months)	69	63	63	76	69	60	62	62	63	73	77
NAFCOM DDT&E + production (excluding Phase A/B) at 70% confidence—for reference	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*$762*	*N/A*	*$910*	*N/A*	*$1,861*	*$1,630*
DDT&E + production in 2007$ including Phase B/C/D for COBRA comparison	*$1,085*	*$933*	*$1,070*	*$1,523*	*$1,237*	*$840*	*$872*	*$939*	*$987*	*$2,223*	*$1,974*
Estimated Phase B/C/D duration (months) including Phase B for COBRA comparison	81	75	75	88	81	72	74	74	75	91	95
Dry mass (kg) model input (provided by the mission teams)	2,551[a]	1,800	1,571	13,740	9,000?	1,409	1,600?	1,611	1,810	1,282	5,882

NOTE: N/A, not applicable. Other acronyms are defined in Appendix G.

[a] Following the release of the report, the DESTINY principal investigator notified the committee that his team misunderstood the committee's request for the payload dry mass, and that the correct figure is 1,784 kg. If this revised figure were to be used in place of the one originally supplied to the committee, the cost estimate in this table for the DESTINY mission would be reduced by approximately 15 percent. This revised number would not change the $1 billion estimated cost which was used to characterize JDEM for the committee's budget analysis, and would have no impact on any of the committee's conclusions, findings, or recommendations.

[b] In the prepublication copy of this report, the "<" sign was accidentally omitted from the table.

continued

TABLE 3.26 Continued

Row 1 (DDT&E + production [excluding Phase A/B] at 70% confidence): This row contains the QuickCost cost model independent estimates for the development and production cost of each mission. It does not reflect partnering credits. The numbers in this row include sufficient reserve to achieve the NASA standard 70% confidence level.

Row 2 (Launch services): This row contains the independent estimate of what the launch costs will be for each mission.

Row 3 (Partnering credits [DOE for JDEM; ESA for LISA]): The study assumed that DOE participation in JDEM will be on the order of $400 million and that ESA participation in LISA will be on the order of $500 million. These values were subtracted from the development cost in the table (as a cash contribution) because the budget analysis that uses the resultant numbers is performed against the committee's extrapolation of the resources available to NASA through FY 2020.

Row 4 (Acquisition subtotal): This row is a subtotal of rows 1, 2, and 3.

Row 5 (MO&DA): This row contains the QuickCost independent estimate of the mission operations and data analysis costs associated with operating the mission control function and data archiving over the operating life cycle of the mission. The Beyond Einstein missions varied in the number of years included in the operating life cycle. The Phase E (MO&DA) costs in this row reflect the number of operating years as defined by the projects themselves in briefings to the committee.

Row 6 (Life cycle cost at 70% confidence): This row is a sum of rows 4 and 5. Because the number predominately includes cost model 70% confidence-level values, it is labeled 70% confidence. This row does not include costs for any necessary work in Phase A or B.

Row 7 (Mission team estimated life cycle cost—for reference): This row represents the life cycle costs as estimated by the mission teams themselves and briefed to the committee. It is included as a comparison to the independent Phase C/D/E estimate in row 6. The mission teams provided cost information in accordance with the RFI (see Appendix E) in real-year dollars, and these figures include costs to partner agencies where applicable (JDEM and LISA).

Row 8 (Estimated Phase C/D duration [months]): The value in this row is the QuickCost cost model predicted duration of full-scale development in months. This value is included in the table because it is used as the time period over which to phase the development cost in the budget analysis.

Row 9 (NAFCOM DDT&E + production [excluding Phase A/B] at 70% confidence—for reference): The NAFCOM results for four missions are documented in row 9 as a cross-check. The costs in row 2 are comparable in content to the costs in row 1. The NAFCOM results are somewhat lower than the QuickCost results but are within an acceptable statistical spread.

Row 10 (DDT&E + production in 2007$ including Phase B/C/D for COBRA comparison): Several discussions and plots of output from the Aerospace Corporation's COBRA model are included in the report. The COBRA model's output is structured differently from that of QuickCost; it includes costs for Phases B, C, and D and provides them in FY2007 dollars. Row 10 converts the QuickCost output in row 1 so that it is comparable to COBRA results reported elsewhere in the report by adding Phase B costs and converting to FY2007 dollars.

Row 11 (Estimated Phase B/C/D duration [months] including Phase B for COBRA comparison): Several discussions and plots of output from the Aerospace Corporation's COBRA model are included in the report. The COBRA model's output is structured differently from that of QuickCost; it includes costs for Phases B, C, and D. Row 11 expands the full-scale duration estimate in row 8 to include Phase B in order to be comparable to COBRA results.

Row 12 (Dry mass [kg] model input): Because mass is a principal independent variable in all the cost models used in this study, it is noted in row 12. The mass values were taken from the mission team briefings given to the committee. Mass is useful in understanding some of the differences in cost. However, since the cost models used other independent variables in addition to mass, it is not fully explanatory. Other variables such as the engineering and manufacturing complexity of the missions can drive cost as much or more than mass.

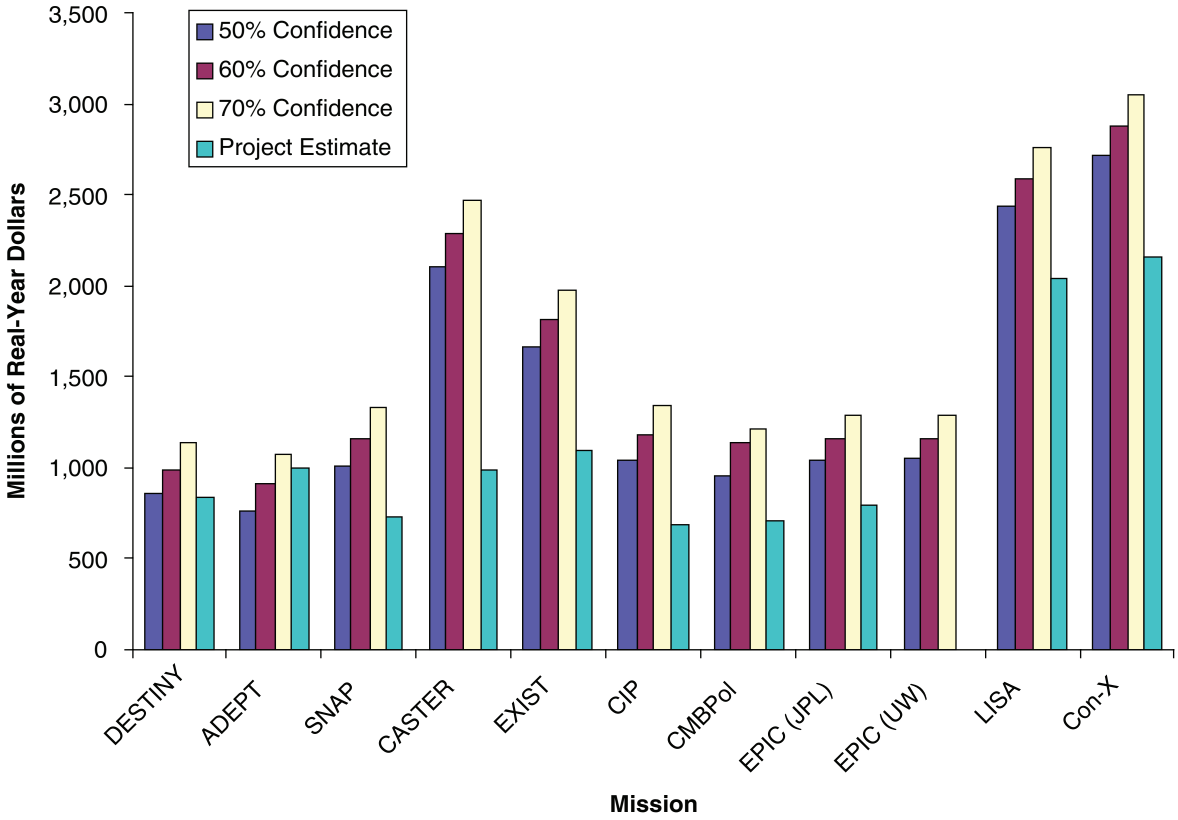

FIGURE 3.1 Ranges of estimated life-cycle costs to NASA. NOTE: Acronyms are defined in Appendix G.

end and culminating with the large observatories (LISA and Con-X) as most complex. Approximate development cost (Phase B/C/D) and schedule regimes are as follows for the Beyond Einstein mission areas:

- Large Observatories (LISA and Con-X): $2 billion; 8 years
- BHFP (EXIST, CASTER): $1.5 billion; 7 years
- JDEM (SNAP, ADEPT, DESTINY): $1 billion; 6 years
- IP (CIP, CMBPol, EPIC-F, EPIC-I): $1 billion; 6 years

Note that the inclusion of launch service ($200 million or $300 million) and MO&DA (which varies, but is on the order of $25 million per year) is above and beyond the development cost numbers noted above.

Budget Analysis

Once the cost and schedule estimates of each individual Beyond Einstein mission were completed, the costs were time-phased against the required schedule span. The committee compared the resulting time-phased cost to the expected available budgets for these missions as currently understood by the NASA advanced budget planning process.

The Beyond Einstein funding wedge is part of the NASA Science Mission Directorate budget. The science budget further subdivides into themes, and Beyond Einstein is part of the astrophysics theme, which also includes general astronomy and astrophysics missions such as the James Webb Space Telescope. At the time of this study,

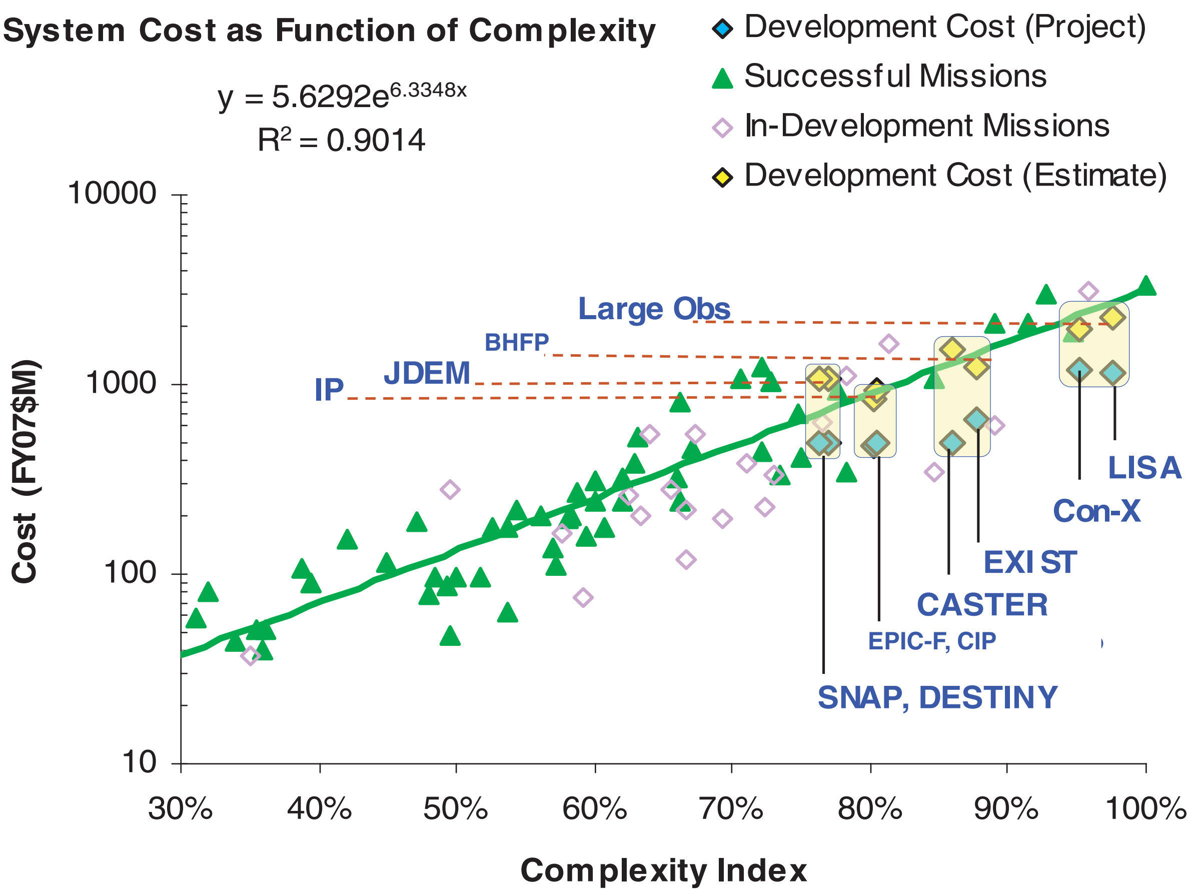

FIGURE 3.2 Comparison of project cost estimates and independent cost estimates to NASA. NOTE: Acronyms are defined in Appendix G.

the Beyond Einstein funding wedge was established through FY 2012. Obviously the budgets for Beyond Einstein that might be available after the FY 2012 budget horizon are not known with certainty. However, it is plausible to extend the FY 2006-FY 2012 budget trajectory into the future using a curve function that assumes neither dramatic increases nor decreases from the FY 2006-FY 2012 trend. Figure 3.4 does that by assuming that the FY 2011-FY 2012 interval slope ($211 million/$157 million, or a 34 percent increase) will continue into the future but will be dampened to more reasonable growth after FY 2013 equal to the square root of the previous year's increase. As can be seen in the figure, this assumption yields an out-year budget curve that extends the general curvature of the FY 2011-FY 2012 interval but with a moderately decreasing slope. Using this assumption allowed the committee's budget analysis to make rational observations about likely starting dates and affordable development intervals of the Beyond Einstein budget scenarios.

For the budget analysis, the committee compared the time-phased cost of various missions to NASA with the available NASA budget. Figure 3.5 shows the 11 Beyond Einstein mission concepts with their nominal time lines shown in comparison against the funding wedge. LISA and the JDEM mission budget profiles were prorated to account for the ESA and DOE contributions, respectively. These contributions were not taken into account when developing the mission cost estimates, but are applied in the budget analysis when comparing the mission cost profile to the available budget.

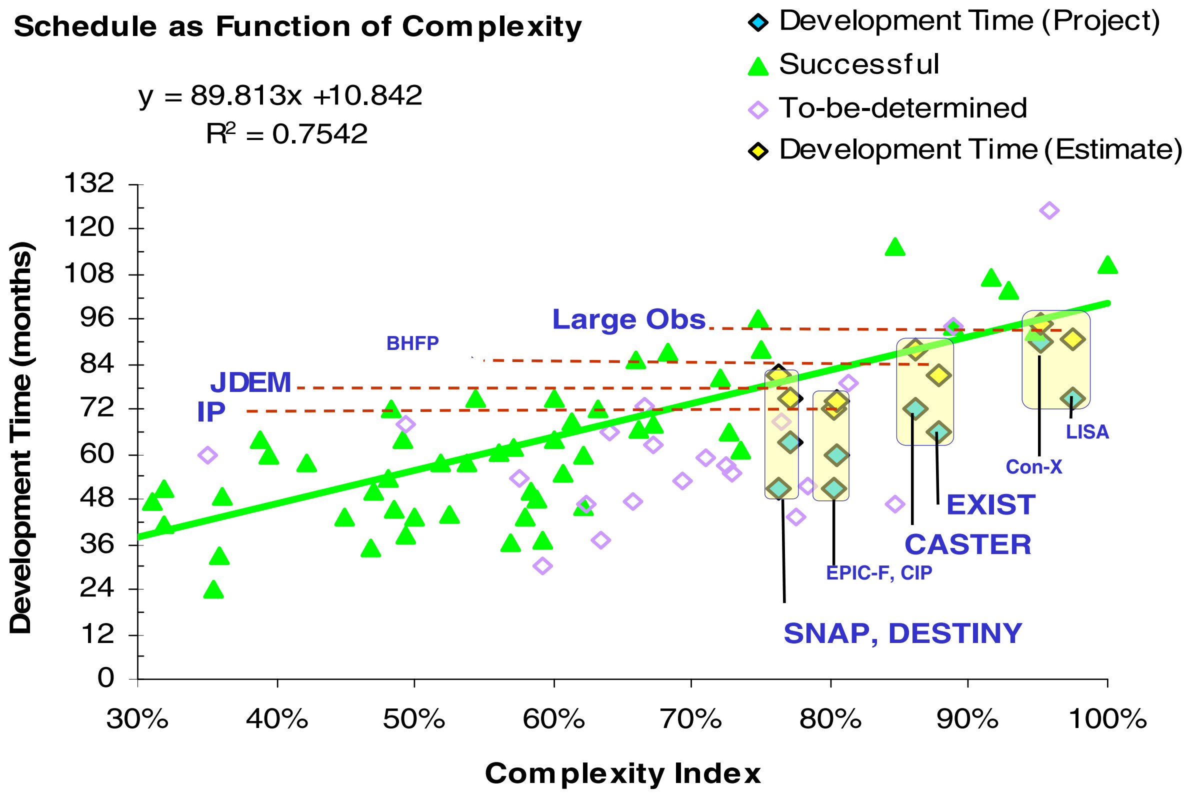

FIGURE 3.3 Comparison of project and independent schedule estimates. NOTE: Acronyms are defined in Appendix G.

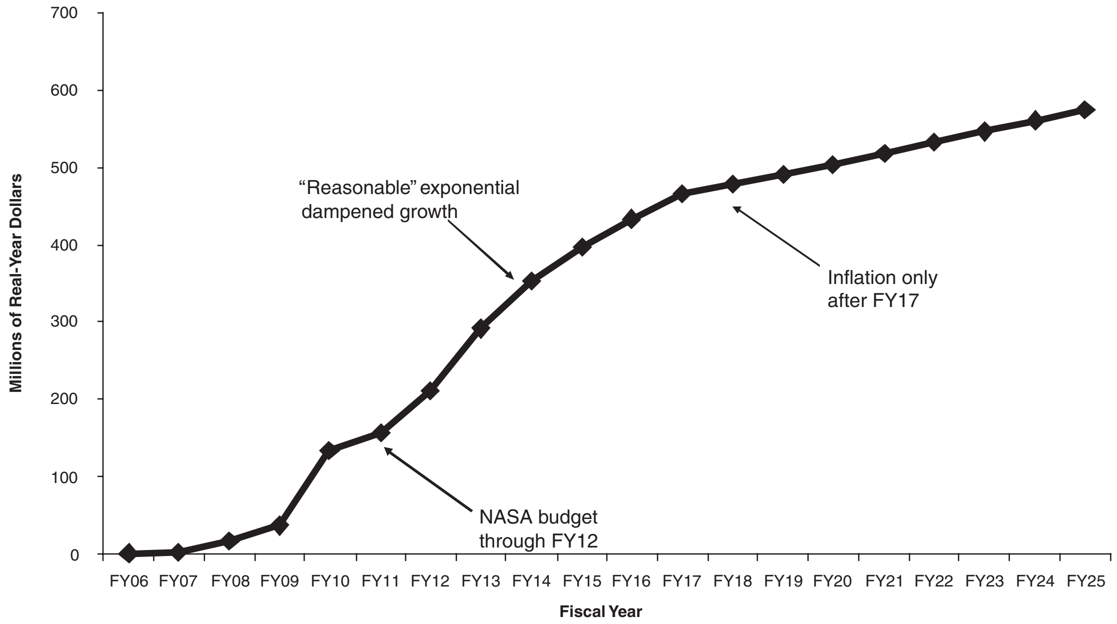

FIGURE 3.4 NASA's assumed Beyond Einstein funding wedge, FY 2006-FY 2025.

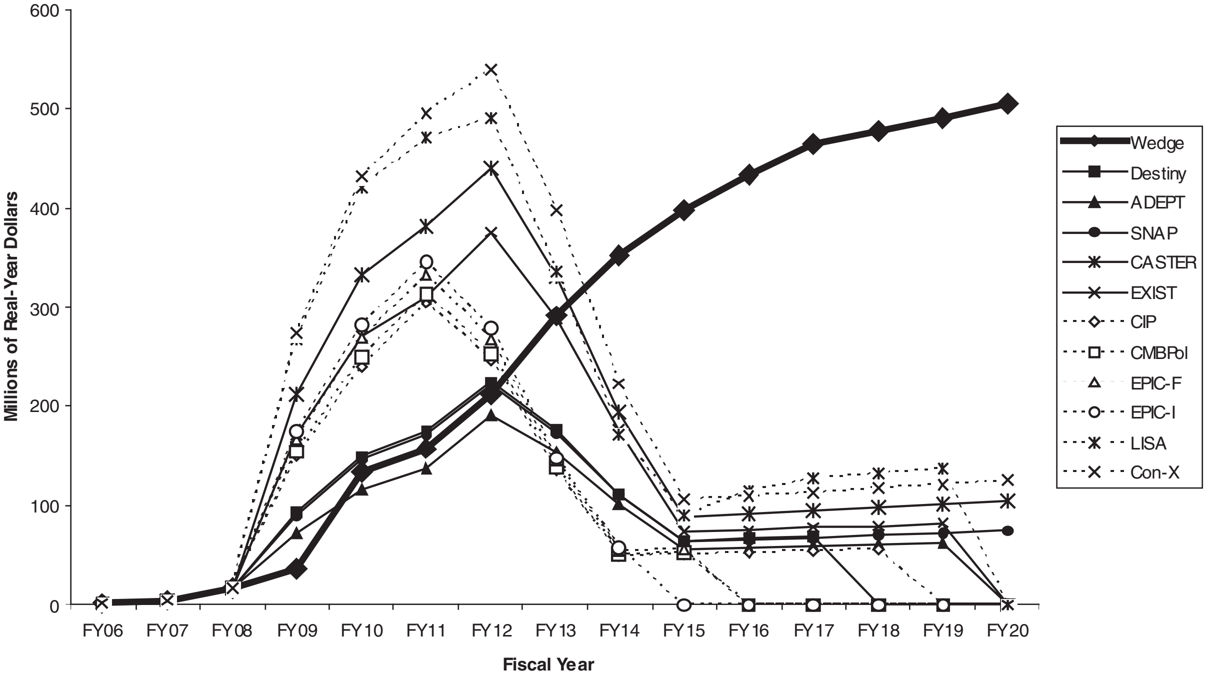

FIGURE 3.5 Cost to NASA of Beyond Einstein mission concepts compared to the NASA budget wedge.

NASA's Beyond Einstein funding wedge through FY 2009 is inadequate to prepare any Beyond Einstein mission for an FY 2009 start without a significant increase in the funding wedge or substantial investment from outside NASA. The JDEM missions (SNAP, ADEPT, and DESTINY) are the notable exceptions compatible with the NASA budget wedge because of the DOE contribution. The available FY 2006-FY 2009 funds total about $60 million. Most NASA science missions spend an amount equal to about 10 percent of their Phase C/D full-scale development (not including launch services) on Phase A/B activities to reach PDR, at which point they are confirmed by NASA management for a new start. In addition, the FY 2009 funding level of $37 million is inadequate to start a billion-dollar-class mission. The first-year funding for such a mission would more normally be $100 million or more.

SUMMARY

The realism of technology and management plans and of cost estimates is a primary consideration called for in the committee's statement of task. The assessment of the five Beyond Einstein mission areas is necessarily comparative. Three specific criteria are used for the assessment: technical readiness, management readiness, and cost realism:

- *Technical readiness elements* are the instrument, spacecraft, operations, and technical margins;
- *Management readiness elements* include team organization, schedule, and other special challenges; and
- *Cost realism* was done as an independent estimation of the probable cost.

Technical Readiness

Black Hole Finder Probes

CASTER There are multiple technical readiness issues with CASTER. The instrument uses new and unproven technologies, the spacecraft design is at a conceptual stage, and it is not clear that any existing launch vehicle can accommodate the CASTER size, length, and associated high-center-of-gravity location. Specifically, more time is needed to develop the detector, the scintillator, and the collimator shielding technique. To achieve the required sensitivity, CASTER will require a very large number of detector modules. Achieving the necessary yield of detectors to meet CASTER's requirements will be a significant manufacturing and production challenge. The CASTER team proposes to use photo-multiplier tubes (PMTs) as the readout sensor. While PMTs have been used many times in space applications, the Burle Planacon tube selected for CASTER is not flight-rated, and there is no flight experience with this device. Similarly, the lanthanum bromide (LaBr^3) scintillators have no flight heritage and are in an early state of development. A significant effort will be required to bring both the PMT and LaBr3 technologies to the level of maturity necessary, TRL 6, to begin a mission.

Additional technology issues include detector shielding and the opaqueness of the coded-aperture mask needed to meet angular resolution requirements at energies up to 600 keV; both the detector shielding and the coded-aperture mask will be difficult to manufacture. The requirements placed on the coded-aperture mask are severe and more challenging than those of any coded-aperture mask flown to date.

The proposed CASTER spacecraft design is at a preliminary stage. The CASTER observatory, which includes the instrument and the spacecraft, is extremely heavy; the structure will present a serious technical challenge to design. In addition, the mass of the CASTER observatory requires the use of the largest U.S. launch vehicle, and even then, it cannot be placed in the desired equatorial orbit.

EXIST The proposed EXIST spacecraft is in the conceptual stage with some basic design trade studies completed. Several of the key instrument technologies are judged to be at TRLs well below 6, and so significant technology development work (high- and low-energy detectors, coded-aperture mask, shielding/anticoincidence system) will be required before EXIST is ready to progress to mission development. The optics for EXIST are in the coded-aperture masks and, while laboratory prototypes have been demonstrated, significant development efforts are still anticipated—that is, the pinhole pattern and the actual laminate construction of the masks for the two telescopes will require significant development. The cadmium-zinc-telluride/application-specific integrated circuit (CZT/ASIC) and silicon detector/readout electronics have heritage from other programs, but the technology development is more complicated than what has been demonstrated in the past, and packaging will be challenging. The packaging of the detector assemblies will be challenging, and the manufacturing of the large number of subsystems will also be a challenge. In addition, the Fast On-board Burst Alert System has to be developed and debugged, and will be a driver for the spacecraft attitude determination and control system.

Constellation-X

The proposed Constellation-X mission is the result of detailed studies and design work. Every major element of the Con-X instruments is at a TRL of 5 or lower, which presents major technology development challenges for the mission. The Con-X observatory employs two telescope systems: the Spectroscopic X-ray Telescope and the Hard X-ray Telescope. The Flight Mirror Assembly optics used in the SXT is driven in large part by the need for large collecting area and high angular resolution. The fabrication of the 10,000 mirror segments, verification of their optical performance, and proper mounting and alignment of the segments to meet Con-X requirements will be challenging. Although significant detailed planning for the FMA has been performed, it is not obvious how much of this planning and the experience of the Con-X mission team members will transfer to the contractor that will be selected to produce the FMA. The SXT instrument, and therefore mission success, depends on the availability of the X-Ray Microcalorimeter Spectrometer. A major XMS challenge is the readout electronics associated with the detectors. In particular, sampling speed combined with the requirement for a very low noise figure are key design drivers for the readout electronics.

The SXT and HXT instruments drive multiple spacecraft design and performance requirements, for example, attitude determination and control, data storage, and thermal considerations.

The Con-X mission has adequate technical margins in most areas. However, the level of maturity of the FMA and the potential increase in mass to address issues in accommodating the XGS and HXT are a concern. The 1 percent mass margin for the proposed launch vehicle on Con-X may not be sufficient for the project.

Inflation Probes

CIP The Cosmic Inflation Probe mission team provided a complete description of its proposed implementation and, in general, makes use of available technologies or technologies being developed for other programs. There are no serious technology readiness issues for CIP, although work remains to be done to determine whether the detector noise figure is adequate at the planned higher operating temperature. The CIP detector uses the same Teledyne Hawaii-2RG HgCdTe detectors currently planned for JWST, but CIP will be operating the detectors at a somewhat higher temperature. The major outstanding issue is whether the dark current level is acceptable at the higher temperature.

There are no unusual or unduly challenging requirements for the CIP spacecraft. The CIP project allocated adequate technical margins in most areas, but did not provide margins for attitude control and data link; however, these areas are not stressing the state of the art and do not raise significant risk issues.

CMBPol The Cosmic Microwave Background Polarimeter mission team provided a concept for its proposed instrument to measure the polarization of the cosmic background, but little detail was provided on the implementation of its spacecraft and the overall mission, although it appears to be based on NASA's Cosmic Background Explorer mission.

The CMBPol instrument uses a variable-delay polarization modulator and a folding mirror to control the entry of stray light into the cooled detector array; similar VPMs have been prototyped at GSFC and are under evaluation, but none has flown in space. The detector challenge will be to keep the noise low enough to provide the sensitivity necessary to measure the polarization of the cosmic microwave background. There is concern about the detailed design of the detector system, particularly the signal-to-noise ratio, and this is an area where an investment of time and money could potentially be put to good use.

EPIC-F The Experimental Probe of Inflationary Cosmology mission team provided a fairly complete description of its instrument, mission, and spacecraft.

The primary area of technical concern is with the instrument. Antenna development for the focal plane array is the major technology issue, as well as integration of the cryogenic optics with the detector system to achieve the required low noise operation. The wave plate technology planned for use in the microwave optics of EPIC-F has been matured to TRL 6 in ground testing. The NTD Ge bolometric detectors are not considered to be a serious challenge; however, packaging may be a challenge for all missions planning on using these detectors to keep the noise to an acceptable level.

The deployable sunshield will require careful design and testing. It is similar to but much smaller than the one being developed for JWST.

The spacecraft requirements for EPIC-F appear to be modest and are not expected to be a challenge. EPIC-F showed good technical margins, although no margins were provided for attitude control and data communications. In addition, the sensitivity needed for the instrument is significantly greater than that needed for previous instruments and will present a very significant technical challenge to meet.

EPIC-I Insufficient information concerning the spacecraft and mission concept was provided for the committee to adequately evaluate the technical readiness of the Einstein Polarization Interferometer for Cosmology.

The project is proposing corrugated horn antennas similar to those flown on COBE. Similar heritage could be made for the bolometers if they are truly close to the NTD Ge devices used for Planck and Herschel or TES devices from SCUBA and GBT.

Joint Dark Energy Missions

ADEPT The Advanced Dark Energy Physics Telescope mission team provided insufficient information for the committee to adequately evaluate the technical readiness of the proposed mission.

The mission will be based on technologies developed for missions such as Swift and the commercial GeoEye imaging spacecraft. They will be using the same Hawaii HgCdTe 2k × 2k infrared detectors that JWST uses, but with the cutoff frequency modified to 2 μm. There is some challenge to this modification, but there are ongoing programs that should demonstrate even lower cutoff frequencies.

DESTINY The Dark Energy Space Telescope mission team provided a complete description of its proposed mission with broad use of proven technologies. Key technologies for the instrument and spacecraft were rated at TRL 6 or higher, with the exception of the detectors, which were rated at TRL 5 by the committee.

The optics required for DESTINY is within the state of the art for size, prescription, and precision. Employing a 1.65 m primary mirror, the optics for DESTINY can be built without any special challenge. The proposed detectors are 2k × 2k Hawaii-2RG devices. While the sensor chip assemblies are very similar to devices on JWST, there are differences, most notably the cutoff wavelength.

The only challenge for the spacecraft is in the area of pointing and stabilization, and depends in large part on the performance of the camera fine-guidance subsystem.

SNAP The Supernova Acceleration Probe mission team provided extensive details on its planned approach, with adequate technical margins in all areas.

SNAP technologies are either mature or progressing toward TRL 6 in well-planned steps. SNAP uses two types of detectors, a Lawrence Berkeley National Laboratory-supplied, radiation-hardened charge-coupled device and a Rockwell- or Raytheon-supplied mercury-cadmium-telluride infrared detector. The ability of LBNL to produce the required number of CCDs in the needed time frame is a concern. The performance of the integrated instrument could be a challenge to maintain low noise levels over temperature. The focal plane plate is about twice the size of existing devices and could present a challenge. All components in the spectrograph are standard and should pose no development risk with the exception of the Image Slicer.

LISA

The Laser Interferometer Space Antenna mission team provided extensive details on the proposed mission. The LISA system will be very challenging to implement, in large part because many of the key technologies are at low TRL levels. These include the Gravitational Reference Sensor, optical systems, laser systems, phase measurement systems, laser frequency noise suppression systems, and micronewton thrusters. The LISA team, however, has laid out a comprehensive plan to mature these key technologies prior to initiating full-scale development for LISA. These plans include the LISA Pathfinder demonstration mission, which will serve to reduce risk and demonstrate on-orbit performance of most of the key technologies.

The optical materials, components, and techniques used in LISA have significant heritage. The LISA Pathfinder optical system (while different in design) will provide significant confidence in the system. The phase measurement system for LISA employs both a photo receiver and a phase meter. Other missions have used similar architectures to the one planned for LISA, and ongoing breadboard testing of both components has been successful to date.

The micronewton thrusters are the most challenging technology development being addressed by the LISA team. The micronewton thrusters must work for the entire life of the mission for LISA to be successful. The lack of endurance testing, the inability to perform qualification-level testing prior to the 2009 time frame (just from a time perspective), and the problems encountered to date indicate that this is a significant risk area with a high degree of difficulty. Three separate techniques are being considered for laser frequency noise suppression.

The LISA spacecraft has been described as a "science craft," which is an accurate description, as the spacecraft bus is built up around the interferometer. The three LISA spacecraft will be separated by 5 million kilometers in flight. Maintaining signal to noise over this arm length and being able to extract phase information from signals with such low amplitude will be extremely challenging. Maintaining the proof mass in the right position will also be challenging, but the initial acquisition, alignment and tracking will be extremely challenging.

Management Readiness

Management readiness elements included team organization, schedule, and other special challenges. Not all of these criteria were discussed by the individual mission teams. A summary of the key points that were presented by the mission teams is included here.

Black Hole Finder Probes

CASTER The CASTER team is a modest-sized team and is well within the experience base of the Southwest Research Institute to manage. There is no known significant foreign contribution planned for CASTER, thus lessening ITAR problems and eliminating the mission's vulnerability to priority changes of foreign governments. The CASTER mission schedule proposes to launch 4.5 years after Preliminary Design Review, which is tight even if progress is made by the mission in raising the Technology Readiness Levels of the elements. The challenging part of the proposed schedule will be to complete the technology development and detector production activities.

EXIST It is assumed that the mission will be managed by NASA's Goddard Space Flight Center, because GSFC has been deeply involved with EXIST for the past few years. The proposed schedule of 4.25 years from PDR to launch is quite tight, given the extent of the detector production effort and the roll-up of instrument assembly into an observatory.

Con-X The Con-X team is led by GSFC, with the mission scientist at the Smithsonian Astrophysical Observatory (SAO). There are no special project management challenges for Con-X. The schedules supplied to the committee focused primarily on technology development schedules.

Inflation Probes

CIP CIP is managed by SAO, with strong support from Lockheed Martin. The proposed schedule shows a PDR in the first quarter of 2010 and a launch in the second quarter of 2013, which is an extremely aggressive schedule.

CMBPol The CMBPol mission was presented as a concept only, and no detailed schedule was made available.

EPIC-F The EPIC-F project will be managed by the Jet Propulsion Laboratory and is certainly within the experience base of missions led by JPL in the past. The EPIC-F team has proposed a 60 month development schedule, which is reasonable based on the complexity of the mission and the current TRLs of the critical technologies. The development of the cryogenics payload will be the most significant schedule challenge for EPIC-F, along with integration of the payload with the commercial spacecraft bus.

EPIC-I The EPIC-I team is led by the University of Wisconsin-Madison with the industrial partners General Dynamics and Ball Aerospace. No information regarding schedule was provided.

Joint Dark Energy Missions

ADEPT ADEPT has a diverse science team from a number of organizations. There was no other information presented relative to team organization and operations.

DESTINY Assuming that the team responsibilities remain unchanged, there are no obvious management challenges to the DESTINY mission. There was very little schedule information provided by the DESTINY team.

SNAP Managing the SNAP project that has international partners as well as two U.S. government centers (GSFC and LBNL) could prove to be a challenge. The proposed schedule shows 4.75 years from the PDR to launch, which is barely adequate development time for a mission of this complexity.

LISA The LISA mission is to be co-funded by NASA and the European Space Agency and is thus dependent on the willingness of each agency to maintain its contribution level and profile through the life of the project. Managing the partnership between ESA and NASA is a major challenge, especially under the constraints imposed by high visibility and ITAR. The LISA mission's critical path is through the development of the micronewton thrusters and the phase measurement systems. LISA did present a very well-organized team with good depth in each technical discipline.

Cost Assessment

Using a consistent methodology, an independent estimate was performed for the purpose of comparison with previous missions of similar scope and complexity in order to provide a realistic expectation of the cost range for each mission concept. While not exacting, relative assessment and comparison with project estimates as available indicates higher costs and longer schedules than previously estimated for each mission.

The committee developed a set of most probable budget profiles for the candidate Beyond Einstein missions. Although some came closer to the Beyond Einstein budget profile than others, the committee concludes that there are realistic options for NASA to initiate JDEM and LISA with or without its partners. As one option, the committee assessed funding profiles against the available NASA funding wedge, taking into account non-NASA budget contributions. While the Beyond Einstein funding wedge is inadequate to develop any Beyond Einstein mission on its nominal schedule, contributions from non-NASA partners, as is the case for JDEM and LISA, could alleviate budget stresses but would require additional management, commitments, and coordination. Furthermore, mission development could be slowed to adhere to the available budget, with the effect of delaying launch.

4

Policy Issues

POLICY CONSIDERATIONS IN MAKING RECOMMENDATIONS

As directed in the statement of task for this study, the Committee on NASA's Beyond Einstein Program made its recommendations based on its assessments of the scientific impact and the technical and management realism of proposed missions. Policy issues are additional considerations, or external factors that provide underlying context and possibly influence the future implementation of committee recommendations.

During its deliberations, the committee identified several policy-related issues relevant to the Beyond Einstein Program. They included the following: implications for U.S. science and technology leadership, program funding constraints, the role of interagency and international partnerships, investments in underlying research and technology and supporting infrastructure, and the impact of International Traffic in Arms Regulations (ITAR). Each issue is addressed in more detail in the sections that follow.

SCIENCE AND TECHNOLOGY LEADERSHIP

An international competition is under way to find answers to questions about the origin, evolution, composition, and behavior of the universe. Because of prior mission successes such as those of the Compton Gamma Ray Observatory, Cosmic Background Explorer, Wilkinson Microwave Anisotropy Probe, Swift, and Chandra, the United States enjoys a substantial lead in applying space research to explore the frontiers of cosmology and high-energy astrophysics. The national priority of this field and the associated level of commitment to pursue Beyond Einstein missions is an important issue. At stake is this nation's leadership role as well as the vitality of research universities and laboratories. It is this vitality that fosters the knowledge base, technology, and prestige with which the United States competes on the world stage. The impact of the efforts vis-à-vis the Beyond Einstein missions is felt far beyond the science goals outlined in this report.

The pursuit of answers to the fundamental science questions at the heart of the Beyond Einstein Program is an awesome responsibility of national leadership. Achievements in Beyond Einstein science, including the rate of progress, depend on an actively engaged and enlightened leadership within the nation's political institutions and scientific enterprises.

PROGRAM FUNDING CONSTRAINTS

The cost realism assessments performed by the committee indicate that the probable costs of Beyond Einstein missions are substantially higher than the current estimates provided by the candidate mission teams. As a result, the committee is concerned that the Beyond Einstein funding wedge provided for its assessment is inconsistent with a healthy long-term program. Assuming that the start of development for a high-priority mission is in 2009, Beyond Einstein Program funding will be severely restricted, potentially crowding out critical research and analysis and technology development needs.

The committee recognizes that the Beyond Einstein funding wedge represents an agreement among NASA, the administration, and the Congress and is viewed as a relatively fixed budget. However, as a result of cost realism assessments, the committee believes that policy makers may need to reconsider the allocation of funds within the budgeting process. NASA may also consider alternative funding sources outside the Beyond Einstein Program. Without such actions, the likely result is that the overall Beyond Einstein Program will be stretched out considerably and difficult to sustain.

PARTNERSHIPS

Two Beyond Einstein missions can be characterized as partnerships: the Joint Dark Energy Mission (JDEM), a joint NASA/Department of Energy (DOE) effort; and the Laser Interferometer Space Antenna (LISA), a partnership between the European Space Agency (ESA) and NASA. NASA's experience with similar interagency and international space missions is wide ranging and generally successful. Both ESA and DOE have similar experiences, including successful partnerships with NASA. Cassini-Huygens is one example of a mission that involved these three agencies. While partnerships do succeed, aligning priorities among these agencies will require substantial management effort by the involved parties. The complexity of the integration and operations of joint missions is an additional concern. Usually, to manage complexity and risk, the focus is on decoupling and simplifying interfaces whenever possible, a task not easily accomplished on LISA.

The NASA/DOE JDEM partnership, although between U.S. government agencies, is not without potential complications. The present arrangement for sharing responsibilities is governed by the DOE/NASA JDEM Strawman Plan,[1] which assumes contributions from each agency in proportion to the role of each in mission development and operation. It would be useful for the two agencies to develop this Strawman Plan into a more detailed agreement, specifically stating the basis for sharing. After a specific JDEM design is chosen, the agencies are expected to develop a funding profile jointly and to agree on a split that reflects the work to be performed by each agency.

The committee recognizes that interagency and international collaboration can, if properly structured, reduce the cost burden on individual agencies, increase the richness of scientific collaboration, and provide larger pools from which to draw technology and talent. The committee also recognizes that such collaboration, if not properly structured, can increase cost and risk by adding bureaucratic hurdles to securing funding, can increase technical and management complexity, and can delay schedule.

The committee assumes that proposed collaborations will be implemented and that partnering organizations and policy makers will successfully follow through on Beyond Einstein mission execution.

INVESTMENTS IN RESEARCH AND TECHNOLOGY AND INFRASTRUCTURE

Ongoing research and technology investments are the glue that holds the space science community together. Research and analysis engender new questions, while technology provides the means to obtain new data and eventual answers. Without continuous investment funding, the quality of the future missions and science results would certainly suffer. The committee is concerned about possible gaps in missions and about funding having an impact on the supply and quality of scientists, and ultimately, on Beyond Einstein science.

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[1] Available at http://www.science.doe.gov/hep/JDEM%20Reports.shtm.

NASA, in collaboration with current and potential partners, should update and build on its 2003 roadmap, *Beyond Einstein: From the Big Bang to Black Holes*, in setting its future plans.[2] An updated roadmap would include greater detail on how specific missions will be planned and implemented, including specific plans for technology development, research and analysis, and education and outreach. Continuous funding support for these areas is necessary to ensure a pipeline of future Beyond Einstein science opportunities.

Several of the proposed mission concepts rely on existing infrastructure outside the Beyond Einstein Program. The committee is concerned that critical infrastructure needed to accomplish these missions must be in place during the period when the Beyond Einstein missions will be operating. These assets include the equivalent of a Deep Space Network with supporting orbital and ground networks, data archival and distribution networks, and high-speed ground links. Investments in the infrastructure that enables researchers to communicate, organize, and share information are crucial to ensuring optimal participation in the research effort. In making decisions about the maintenance and upgrades of existing infrastructure, NASA must include the projected requirements for Beyond Einstein missions.

INTERNATIONAL TRAFFIC IN ARMS REGULATIONS

The committee is concerned that ITAR could impede cooperation or collaboration with Beyond Einstein international partners. Of particular concern are LISA and the JDEM mission candidate, SNAP, proposing international collaboration. Should a mission experience serious ITAR issues regarding the exchange of technical information or hardware, schedule and cost impacts could be significant.

Among Beyond Einstein missions, LISA is the most vulnerable to potential ITAR problems. LISA's greater susceptibility to ITAR issues is due to the scope and complexity of the technical interfaces between the NASA and ESA contributions. While LISA and other mission teams proposing significant international participation are proactive in addressing export control issues, these issues remain a programmatic risk that NASA and ESA must carefully manage.

NASA's experience in managing international collaborations (e.g., the International Space Station, the Hubble Space Telescope, and the Cassini-Huygens mission) speaks to its ability to overcome ITAR impediments, although sometimes with difficulty. Policy makers should carefully review the efficacy of the current application of export control regime as it applies to international scientific missions.

SUMMARY AND CONCLUSION

The policy areas of interest addressed above are fairly representative of issues and concerns faced by cutting-edge space sciences missions. Although important and challenging, none is considered an insurmountable barrier to success. And while science, technology, and operations issues could present additional complications and risks, the committee believes that the space sciences community is capable of responding to these challenges. Obviously, partnerships have been and will continue to be successful, but they do require substantial attention.

In conclusion, the United States and its partners are in an enviable position of possessing multiple, high-quality mission concepts to answer Beyond Einstein questions. To succeed, however, sponsoring agencies must quickly align behind the highest priorities identified for the Beyond Einstein Program while continuing a robust program that invests in future mission technologies.

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[2] NASA, 2003, *Beyond Einstein: From the Big Bang to Black Holes*, Structure and Evolution of the Universe Subcommittee Report, Washington, D.C., January.

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Findings and Recommendations

ASSESSING THE BEYOND EINSTEIN MISSIONS

NASA and the Department of Energy (DOE) have requested that the National Research Council (NRC) assess the Beyond Einstein missions, with the following charge:

> 1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder Probe) and *recommend which of these five should be developed and launched first,* using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:
>
> - Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
> - Realism of preliminary technology and management plans, and cost estimates.
>
> 2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

Many NRC panels are tasked to judge scientific excellence within a single scientific discipline. NASA's Beyond Einstein Program is designed to be at the intersection of physics and astronomy and is a subset of each discipline. Therefore, the Committee on NASA's Beyond Einstein Program: An Architecture for Implementation had to take into account the goals of two scientific disciplines and their methods of working. Responding to the charge, the committee also based its conclusions on a second dimension: the technical and scientific readiness of the proposed missions.

To deal with its complex charge, the committee included not only members who are experts in both physics and astronomy, but also individuals with great experience in spacecraft development and program implementation. The blend between scientists and engineers has led to an extraordinarily vigorous and productive assessment effort. A necessary tension between scientific attraction and timely implementation has been at the center of all the committee's discussions.

The five mission areas in NASA's Beyond Einstein Program plan are in very different stages of technical development. Some of the mission candidates have been under study for more than 10 years, while others are at an early phase of conceptual design. Each mission candidate has its own balance of interest to the astronomy and physics research communities. The committee considered them all in as objective and transparent a way as possible, even if there is no perfectly commensurate basis for comparison. The committee recommends one mission area to be implemented first, but as noted in Chapter 2, each area makes an important contribution to Beyond Einstein research goals. Each mission area needs to receive appropriate support in order to prepare for consideration by NASA and the next astronomy and astrophysics decadal survey of the National Research Council. Some specific suggestions for providing such support are contained in the subsection below entitled "Beyond Einstein Cost Assessment Summary."

The committee considered many ways to approach the intertwined scientific, engineering, and programmatic issues implied by its charge, and it has endeavored to respond to its entire charge as faithfully as possible. The committee firmly believes that, while the statement of task required it to recommend one mission area for a fiscal year (FY) 2009 new start, all of the Beyond Einstein mission areas address key scientific questions that take physics and astronomy beyond where the century of Einstein left them. Furthermore, the scientific issues are so compelling that Beyond Einstein research will be pursued for many years to come. Therefore, the committee responds to the task in the conviction that it is recommending the first element of an enduring program, and not the only and last mission in Beyond Einstein science.

How the Recommendations Evolved

The committee started with systematic consideration of each of the 11 mission candidates identified thus far in the five mission areas in the Beyond Einstein Program. Since the task of the committee was to select one of the five mission areas, rather than one of the 11 potential mission candidates, the mission candidates were considered only as representatives of the capabilities that could be provided by a mission area. The committee was aware that NASA typically makes a broad request for proposals in order to encourage the most up-to-date scientific strategies and technological approaches. The committee heard at least two presentations from each mission candidate team, in addition to presentations from individual scientific leaders, and had conversations with the broader scientific community in town hall meetings across the United States (see Appendixes C and D). Subsequently, the committee asked clarifying questions of each team and included the team's written responses in the assessment process. Agency leaders in NASA, DOE, and the European Space Agency (ESA) provided additional presentations. Using these inputs, the committee assessed each mission candidate for its scientific excellence, its response to Beyond Einstein goals, its competition from other space- and ground-based projects in the United States and abroad, its scientific and engineering complexity, its cost and related programmatic implications, its stage of development and overall readiness, and pertinent individual factors. In making its recommendations, the committee considered the potential contribution of ground-based capabilities to address the scientific questions posed to the Beyond Einstein Program. The committee assumed that existing and proposed ground-based capabilities such as the Large Synoptic Survey Telescope and the Laser Interferometer Gravitational Wave Observatory (both supported by the National Science Foundation [NSF]) will be funded and operated as planned. While it is impossible to predict what discoveries will be made by ground-based systems, the projected performance of ground-based systems was compared with the expected performance of Beyond Einstein missions. This assessment culminated in draft individual write-ups for each mission candidate.

The committee carried out these steps before any formal discussion of the first part of its charge. The committee gave each mission candidate its full attention and developed a balanced view of the entire Beyond Einstein Program before addressing its main charge. Only after the drafting of the broad assessment of each mission as required in the second half of the charge did the committee start a comparative discussion to identify the main competitors for the FY 2009 start.

The Beyond Einstein Program

The committee found that all five Beyond Einstein mission areas contain scientifically pioneering, publicly appealing, and technically challenging mission candidates. As discussed in detail in Chapter 2, the committee assessed the 11 mission candidates according to their contributions to Beyond Einstein science and their broader scientific impact. For both Beyond Einstein science and the broader scientific impact, the committee assessed three factors: the potential for revolutionary science, science readiness and risk, and mission uniqueness. Chapter 3 contains the committee's assessment of technical readiness for each of the 11 mission candidates.

After the scientific and technical assessments of all five mission areas were completed, two stood out for the directness with which they address Beyond Einstein goals and their potential for broader scientific impact: the Laser Interferometer Space Antenna (LISA) and the Joint Dark Energy Mission (JDEM). The committee was unanimous that in fulfilling its charge, it should choose between these two. To put this result and the findings in the next subsection in context, the committee's assessments of each of the Beyond Einstein areas are briefly recapitulated here.

The proposed Black Hole Finder Probe (BHFP) mission candidates seek to detect thousands of hard x-ray sources and to determine the population distribution of massive black holes in external galaxies and of the more luminous x-ray binaries in our own Galaxy. The Inflation Probe (IP) mission candidates seek to study for the first time the conditions in the early universe when it suddenly expanded by 30 orders of magnitude, creating the particle populations that led to the particles and radiation observed today in the present universe. These two mission areas address important Beyond Einstein questions. However, because of scope and technical readiness issues, they fell behind the two leaders in the discussion.

The Constellation-X (Con-X) mission candidate has been designed to be a general-purpose astrophysical observatory. It will unquestionably enable important progress in many fields of astrophysical research. Its broad significance to astronomy is highlighted by the fact that Con-X was second in priority to the James Webb Space Telescope (JWST), now under construction, in the 2001 astronomy and astrophysics decadal survey.[1] The contributions of Con-X to Beyond Einstein science, though not the principal drivers of the mission design, will be significant, but not as decisive as the contributions of the two leaders.

Con-X is a very well developed mission, and at present there exists a large pool of x-ray astronomers and technical expertise for building and using Con-X. One concern is that this workforce may dissipate if the construction of Con-X is delayed indefinitely; also, the very broad scientific contributions of Con-X, both within and beyond the Beyond Einstein areas, would be postponed. Similar concerns apply to potential delays in most mission projects.

LISA is an extraordinarily original and technically bold mission concept. The first direct detection of low-frequency gravitational waves will be a momentous discovery, of the kind that wins Nobel Prizes. The mission will open up an entirely new way of observing the universe, with immense potential to enlarge understanding of both physics and astronomy in unforeseen ways. LISA could be the first to detect gravitational waves from the merger of massive black holes in the centers of galaxies or stellar clusters at cosmological distances, as well as waves generated by stellar mass compact objects as they orbit and fall into massive black holes. An optical identification of such sources would provide an absolute measurement of dark energy. If the committee's charge had been to design a complete multiyear, multimission program addressing comprehensive Beyond Einstein goals, LISA would have been its flagship mission.

Any leadership program addressing Beyond Einstein goals must have a state-of-the-art investigation of dark energy. With any mission clarifying previously unknown properties of 70 percent of the mass-energy in the universe, the potential for fundamental advancement of both astronomy and physics is quite high. For the United States, that mission will be the winner of the JDEM competition. Based on the mission candidates reviewed thus far, JDEM will set the standard in the precision and technical reliability of its determination of the distribution of dark energy in the distant universe. The key dark energy parameter will be measured with an improvement of at least a factor of 10 over today's precision and is likely to exceed the precision attainable by the projects that will be completed in the next decade. Space observations have the potential to collect more data with fewer instrument uncertainties than currently foreseen ground observations, so that a JDEM mission should be a technically secure platform for whatever comes after it in dark energy science.

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

A JDEM mission would bring substantial benefits to general astronomy. All three JDEM mission candidates propose very large surveys by meter-class infrared (IR) space telescopes. Each proposes to collect an unprecedented volume of data, which would enrich the understanding of many topics in extragalactic astronomy, and especially galaxy formation and evolution. After the Hubble Space Telescope (HST) retires, there will be no diffraction-limited optical or near-IR telescope in space. The low backgrounds and large fields of view (FOVs) offered by two of the JDEM candidates would provide the largest quantity thus far of highly detailed information for understanding how galaxies form and acquire mass. The goal of determining the distribution of dark energy with unprecedented precision would drive astronomers' understanding of supernovas and weak-lensing systematics to new levels of precision. There has never been a full-sky spectroscopic survey from space, so the broad discovery potential enabled by this third candidate approach to dark energy determination would be very large. The committee notes that the report *Connecting Quarks with the Cosmos*[2] strongly supported both JDEM and Con-X. The report *Astronomy and Astrophysics in the New Millennium*[3] ranked Con-X as the second-highest-priority new major space initiative (after JWST). However, no prioritization of all the Beyond Einstein missions against one another has ever been done.

The committee compared the JDEM mission concepts with the future ground-based Beyond Einstein-type initiatives known to it (see the subsections "Scientific Context" and "Science Readiness and Risk" in Chapter 2). While some duplication in measurements was identified for the relevant time frame and while ground results are expected to improve over time, ground-based measurements will find difficulty competing with the sensitivity and volume of space measurements. Ground- and space-based measurements in combination, however, were found to be complementary.

The success of LISA depends on the reliable operation of several critical technologies. One relates to the LISA proof masses that respond to gravitational waves and must be protected from nongravitational disturbances. Electrostatic sensors have to locate the proof mass and signal low-force micronewton thrusters to nudge the spacecraft and keep the proof mass at the center of its chamber in a purely gravitational orbit. The ESA, in collaboration with NASA, will launch a one-spacecraft LISA Pathfinder in late 2009 to evaluate in space the precision and reliability of the disturbance-reduction system. Assessing this technical risk is a precursor to ESA's decision to proceed with the three-spacecraft LISA mission jointly with NASA.

The LISA Pathfinder results will only be available after 2009, and a decision to propose a 2009 new start in the U.S. budgetary process would have to be made in the absence of Pathfinder results. The committee believes that it is more responsible technically and financially, and therefore more credible, to delay a decision on a LISA new start until after the results of the Pathfinder are taken into account. As discussed in the next major section, "Moving Forward with the Beyond Einstein Program," it would be prudent for NASA to invest now in further LISA risk reduction and technology development, to help ensure that NASA is in a position to proceed with ESA to a formal LISA new start at the earliest opportunity after the Pathfinder flight.

The JDEM mission candidates proposed thus far, while by no means routine, are based on instrument and spacecraft technologies that either have been flown in space or have been developed in other programs. In some ways, they have had their "pathfinders" already. These precursors give the committee confidence that a JDEM mission selected in 2009 could proceed smoothly to a timely and successful launch. Nonetheless, because the field of dark energy is developing rapidly, a request for proposals that is open to a broad range of mission concepts is advisable.

The committee, mindful of its responsibility to the entire Beyond Einstein Program, is satisfied that a JDEM mission, given its fundamental significance and broad astronomical applicability, would be an excellent way to launch a new program of research that can produce important results for decades to come.

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[2] National Research Council, 2003, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C.

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

Major Findings

In light of the considerations summarized above and described in considerably more detail in the preceding chapters, the committee offers the following major findings and 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 Program 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 (BE) missions. While Con-X 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 that will open up an entirely new way of observing the universe, with immense potential to enlarge the 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 that 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 the 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 candidates identified thus far are based on instrument and spacecraft technologies that either have been flown in space or have been extensively developed in 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.

Principal Recommendations

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 proposals should be (1) to determine the properties of dark energy with high precision and (2) to enable a broad range of astronomi-

cal 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 next NRC decadal survey of astronomy and astrophysics.

MOVING FORWARD WITH THE BEYOND EINSTEIN PROGRAM

Summary Assessment of the Beyond Einstein Mission Set

As indicated at the beginning of this chapter, the second task element of the committee's charge was to "[a]ssess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions." This task element was intended to "assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the [astronomy and astrophysics] Decadal Survey."

The committee's assessment of the 11 mission candidates considered scientific importance, technical readiness, and probable cost. 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. Additionally, LISA needs continued support until NASA initiates a post Pathfinder mission start for LISA.

The scientific importance of the remaining three mission areas—Black Hole Finder Probe, Constellation-X, and Inflation Probe—was also all assessed by the committee as making an important contribution toward answering the Beyond Einstein questions as well as to other important issues in physics and astronomy. These mission areas warrant funding for technology development between now and the next astronomy and astrophysics decadal survey, although this funding may not fit into the Beyond Einstein funding wedge used in this assessment.

Con-X has the potential to make enormously broad contributions to many areas of astronomy and physics. However, Beyond Einstein research is not its sole justification or its primary benefit to the science community. Although the funding would not fit within the current Beyond Einstein budget profile, an aggressive program of technology development should be continued for Con-X to prepare for a new start in the next decade if Con-X is ranked highly by the next astronomy and astrophysics decadal survey (as it was by the previous decadal survey[4]).

The remaining BHFP and IP mission areas are most appropriately funded through other sources, such as the Astrophysics Research Grants Program, at least at the level needed to enable the mission teams to be competitive in the upcoming astronomy and astrophysics decadal survey.

Beyond Einstein Cost Assessment Summary

In order to evaluate the realism of the mission teams' current cost estimates for their respective Beyond Einstein candidates, the committee developed an independent estimate and assessed the probable cost range for each mission. The committee assessment of the probable cost range for each candidate mission was also compared with previous missions of similar scope and complexity. The mission team's estimate and the committee's assessment of the probable cost range for each candidate Beyond Einstein mission are provided in Chapter 3. While not exacting, the committee's assessment indicates higher costs and longer schedules than currently estimated by the mission teams.

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

As presented in the preceding section, the committee recommends that JDEM start development with the Beyond Einstein funding wedge that starts in FY 2009 and that NASA continue critical technology development for LISA to be ready for the results of the LISA Pathfinder mission. In addition to the probable cost range, the committee assessed the most probable development funding profile required for each of the candidate missions against the NASA Beyond Einstein funding wedge and used these data to assess how the JDEM and LISA profiles fit within this wedge. DOE expects to cofund JDEM up to approximately $400 million, and ESA is planning $500 million for LISA.[5,6]

The committee's assessment showed that JDEM is the only mission that could be developed on its nominal schedule within the NASA Beyond Einstein funding wedge, based on the assumed DOE contribution. With a compatible fiscal year funding profile from DOE and ESA, or by adjusting the JDEM and LISA development schedules to better fit the NASA funding wedge, these missions could be carried out within the currently forecasted NASA contribution.

The committee assessed two scenarios that could enable the recommended JDEM and LISA developments. The only quantitative funding profile data provided to the committee were those of the NASA Beyond Einstein funding wedge for FY 2009-FY 2012. Therefore, in order to analyze the scenarios, the committee extrapolated this profile through the development and launch of JDEM and LISA.

For Scenario A, Figure 5.1 clearly shows that, based on the committee's assessment, starting JDEM development in FY 2009 and launching in FY 2015 will not fit within the current NASA Beyond Einstein funding wedge, nor will it support concurrent NASA funding for critical technology development for LISA. Further, given the large mismatch between the probable JDEM budget fiscal year requirements and the available funding wedge, this will be the case even with no investment in LISA during the FY 2009-FY 2011 time frame.

For Scenario B, Figure 5.2 shows that by delaying the full start of JDEM by 2 years and LISA until FY 2014, JDEM and LISA could fit within the committee's forecast of the Beyond Einstein funding wedge. The committee does not recommend that this profile necessarily be followed, and leaves the program implementation to the agencies involved. This scenario is provided as evidence that there is at least one reasonable scenario for implementing the committee's recommendations within the NASA Beyond Einstein funding wedge.

According to information provided to the committee by DOE, DOE funds are expected to cover 7 years and to support a 2-3 year JDEM research and development phase and a 4-5 year construction phase.[7] Depending on the fiscal year funding profile, the DOE contribution could enable a JDEM start date closer to and possibly in FY 2009. ESA told the committee that its funding was expected to be able to support a 2018 launch and therefore could be expected to be able to support a more aggressive LISA development schedule than the NASA budget alone would, possibly as early as FY 2014.

Summaries of Mission Readiness

This subsection summarizes the committee's assessment of the scientific and technical readiness to begin development in FY 2009 toward the launch of the missions for each of the Beyond Einstein candidate mission areas: Black Hole Finder Probe, Constellation-X, Inflation Probe, JDEM, and LISA. As discussed below, the committee strongly believes that the future technology investment is required and warranted in all of the Beyond Einstein mission areas. The current Beyond Einstein budget profile will not support technology development beyond JDEM and LISA. In particular, the committee believes that after funding to start JDEM, the next-highest priority for funding from the funding wedge is for acceleration of the maturation of mission-critical LISA technologies that

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[5] Kathy Turner, Program Manager, Office of High Energy Physics, Department of Energy, "Note to BEPAC Regarding DOE's JDEM Plans," e-mail communication, March 30, 2007.

[6] European Space Agency LISA budget data provided to the committee by David Southwood, ESA Director of Science, in discussions on ESA's Astrophysics and Fundamental Physics Program, April 5, 2007.

[7] Kathy Turner, Program Manager, Office of High Energy Physics, Department of Energy, "Note to BEPAC Regarding DOE's JDEM Plans," e-mail communication, March 30, 2007.

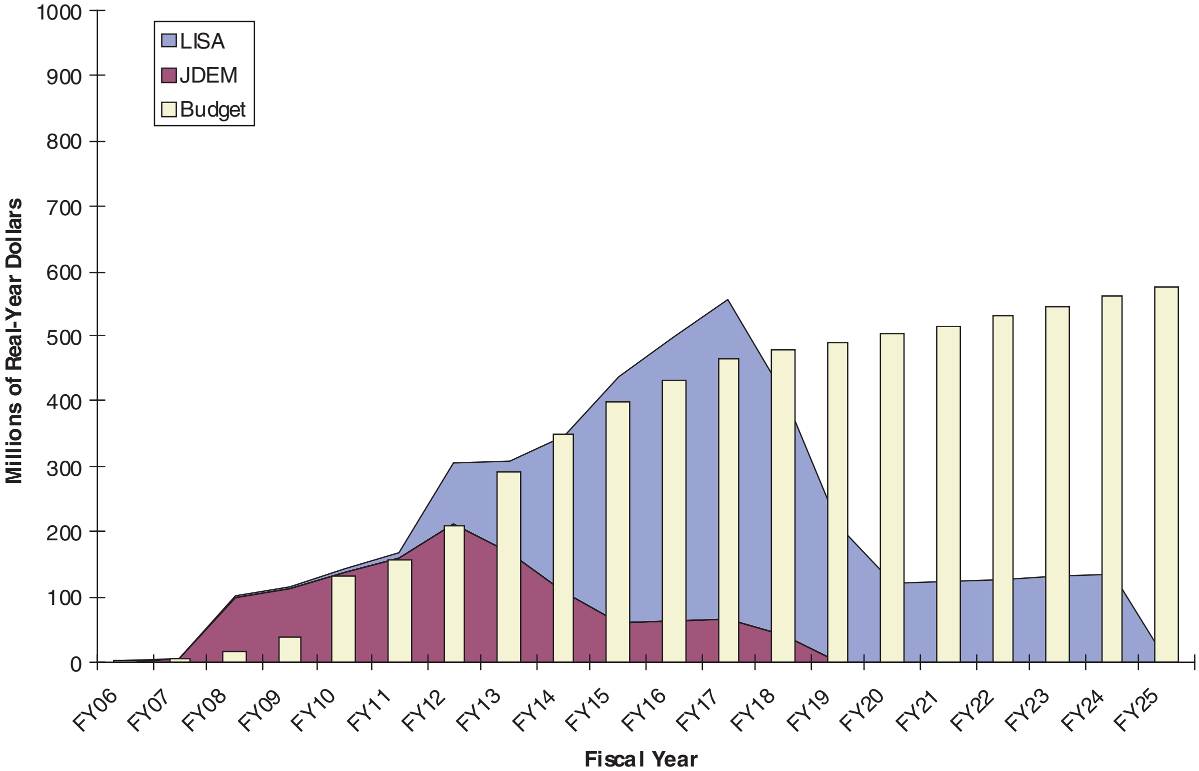

FIGURE 5.1 Scenario A: Cost to NASA of the committee-recommended program versus the projected NASA Beyond Einstein budget. NOTE: JDEM, Joint Dark Energy Mission; LISA, Laser Interferometer Space Antenna.

are currently at low Technology Readiness Levels (TRLs). Technology development for the other mission areas should continue to be supported in the broader astrophysics program.

Black Hole Finder Probe

Science Readiness Assessment Summary The Black Hole Finder Probe (BHFP) is one of the three Einstein Probes discussed in the original Beyond Einstein roadmap published in 2003. BHFP is designed to find black holes on all scales, from one to billions of solar masses. BHFP will observe high-energy x-ray emission from accreting black holes and explosive transients and address a key Beyond Einstein question, How did black holes form and grow?

As described in Chapter 2, BHFP will be unique among current or planned missions in high-energy x-ray sensitivity combined with a large FOV 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 directly impact a number of important astrophysical questions. BHFP will provide a unique window into the properties and evolution of astronomical objects whose physics is dominated by strong gravity.

The committee was presented with two proposed missions, EXIST (Energetic X-ray Imaging Survey Telescope) and CASTER (Coded Aperture Survey Telescope for Energetic Radiation). These two missions are both wide-field coded-aperture hard x-ray survey telescopes, differing primarily in their selection of detector material.

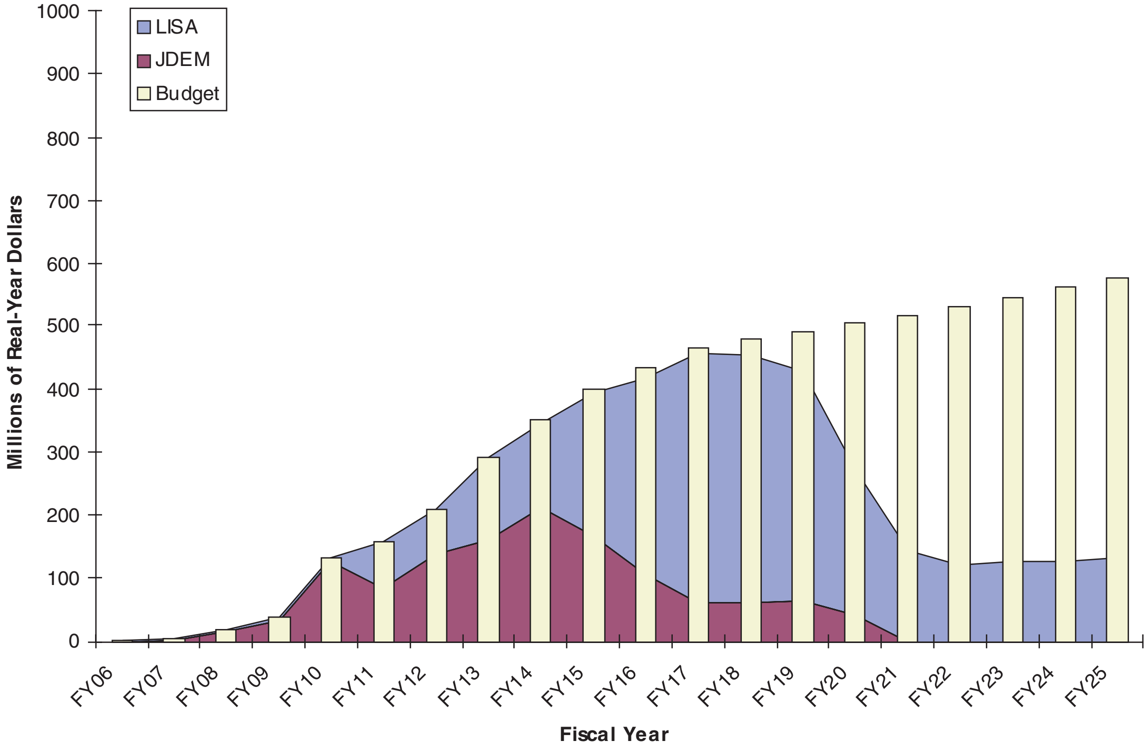

FIGURE 5.2 Scenario B: Cost to NASA of the committee-recommended program phased to fit within the projected NASA Beyond Einstein budget. NOTE: JDEM, Joint Dark Energy Mission; LISA, Laser Interferometer Space Antenna.

The committee notes that the BHFP, as embodied in EXIST, is the only Einstein Probe that was specifically recommended in the 2001 decadal survey report, *Astronomy and Astrophysics in the New Millennium*.[8]

The science risk for BHFP is rather high (see the section "Black Hole Finder Probe" in Chapter 2). 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 multiwavelength observational data and theoretical advances (e.g., in black hole accretion modeling) will be necessary for BHFP to realize its full scientific potential.

Technical Readiness Assessment Summary CASTER and EXIST have both obtained program management and institutional support. CASTER has more technology maturity challenges, as the detector technology in general is at lower TRLs than that for EXIST, as discussed in Chapter 3. The large area of solid-state detectors and the enormous number of electronic readout channels will be a major implementation challenge for EXIST. Both programs have experienced instrument development teams and good risk-mitigation plans; however, more detailed design studies are needed to enable quantitative studies of how to reduce cost by reducing scope. The committee concludes that continued funding from the NASA Astrophysics Research Grants Program for detector development is consistent with the time scale for this mission and that the technology is sufficiently mature to allow an early selection of a single technology for a hard x-ray survey telescope.

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

The overall mission costs for both of the BHFP mission candidates are higher than originally envisioned. BHFP was originally proposed as one of the three Einstein Probes in the Beyond Einstein roadmap. These were envisioned as medium-scale missions that could be executed much more rapidly, and for considerably less money, than the flagship LISA and Con-X missions. However, the BHFP probe concepts now have costs that the mission teams estimate are in the vicinity of a billion dollars, and a much higher independent assessment of their probable cost range is described in Chapter 3; they are quite massive spacecraft that require expensive launch vehicles in the Atlas V class. The trade-off of sensitivity, detector area, and observing time should be carefully considered, and a smaller telescope should be studied to find less expensive ways to carry out the most important BHFP science within a smaller cost envelope.

Constellation-X

Science Readiness Assessment Summary As described in the section "Constellation-X" in Chapter 2, the committee's assessment is that Con-X's primary strength is in 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. Although the capabilities of Con-X represent an evolution of x-ray satellite technology, Con-X's very large collecting area and high-resolution spectrometry capability could lead to fundamental discoveries. In addition to the chances for serendipitous discoveries, the Con-X general observer program will harness the ingenuity of the entire astronomical community. The committee believes that, because of its heritage, Con-X does not involve a significant risk to being able to accomplish the planned key science project goals or to providing the x-ray community with a highly productive next-generation general-observer x-ray facility capable of both fundamental and serendipitous discoveries.

Technical Readiness Assessment Summary Con-X is one of the best studied and tested of the missions presented to the committee. Much of this can be attributed to the heritage of the program management, flight technology, strong community support, and, finally, significant resources for technology and mission development.

Aside from the well-known risks of satellite implementation, a number of technical risks have been called out by the Con-X candidate mission team and also discussed in Chapter 3. Chief among these is the achievement of the needed mirror angular resolution and the development of the position-sensitive microcalorimeters. 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 these technologies will limit the main science goals of the observatory.

The committee notes that the technological requirements to achieve the mission goal appear to have been purposely kept conservative. The positive side is that the path to achieving the requirements (such as an angular resolution of ~15 arcsec) is well defined. The significant progress achieved both at the laboratories and by university-based groups indicates that a more aggressive influx of resources in key areas such as the mirror development, staged cooler system, and large microcalorimeter arrays will be of significant benefit to developments in these areas.

Con-X development activities need to continue aggressively in areas such as achieving the mirror angular resolution, cooling technology, and x-ray microcalorimeter arrays to improve the Con-X mission's readiness for consideration in the next astronomy and astrophysics decadal survey. The committee, however, does not believe that the current Beyond Einstein NASA funding 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

Science Readiness Assessment Summary "Inflation," the term for an exponential expansion that, according to the Inflationary Big Bang Model, took place in an early era of the history of the universe, was proposed in order to solve several fundamental problems in cosmology. During the inflationary era, matter and radiation were created in the universe. The accelerating expansion that occurred during the era of inflation may have similarities with the accelerating expansion that is occurring today and that is attributed to the presence of dark energy throughout the universe. A deeper understanding of the cause of inflation and dark energy is needed in order to allow an exploration of that similarity. Studying inflation may lead to an understanding of the source of the largest structures in the universe, which appear to be linked to quantum fluctuations and phenomena at the smallest scales. An understanding of the inflationary period would give profound insights into both physics and astronomy. Understanding this era is central to the Beyond Einstein goals. The Inflation Probe directly addresses the specific Beyond Einstein question, What powered the big bang? The theoretical framework for understanding the results of both the cosmic microwave background (CMB) and high-redshift galaxy observations is already in place. The observations made by the Inflation Probe will fit readily into models of the universe and provide useful constraints on cosmological parameters.

The committee assessed four candidate IP missions for the Beyond Einstein Program. The science and measurement techniques for these probes are discussed in Chapter 2. Three of these are aimed at learning about the inflationary period using the signal imparted on the polarization of the CMB radiation by gravity waves induced during the inflationary period; the fourth candidate mission uses the effect that the inflation potential has on the primordial density-fluctuation power spectrum that describes the amount of structure in the universe at various length scales. The specific IP missions assessed by the committee are these:

- CMB experiments:
  —*Experimental Probe of Inflationary Cosmology (EPIC-F)*, which employs six 30-cm telescopes, each at a different frequency band, with a total of 830 bolometer detectors;
  —*Einstein Polarization Interferometer for Cosmology (EPIC-I)*, which is a Fizeau interferometric instrument with a synthesized beam resolution of 1° and 1,024 detectors; and
  —*Cosmic Microwave Background Polarimeter (CMBPol)*, which uses about 1,000 bolometers and has a spatial resolution of about 1°.
- *Cosmic Inflation Probe (CIP)*, which consists of a 1.8-meter cooled telescope with a slitless grating spectrometer with a spectral resolution of 600 operating at wavelengths from 2.5 to 5 micrometers.

The key measurement for the three CMB IP candidates is to determine the (B-Mode) CMB polarization due to gravity waves from the inflationary era. As discussed in Chapter 2, one concern about the B-mode polarization is that the B-mode power varies as the fourth power of the energy scale during inflation, so there is only a 3× range in energy scale between the current limits on the B-mode power and the likely detection limits of the Inflation Probe. Mitigating this concern is the fact that at the current best estimates for the spectral index of the primordial power spectrum, the energy scale for inflation might be in this range for typical inflation models, and the CIP mission team proposes to measure this spectral index to much greater precision.

Technical Readiness Assessment Summary The CIP concept and mission design is a modification of existing missions. The detectors are very similar to the JWST Near-Infrared Camera (NIRCAM) long-wavelength detectors, but CIP requires eight times more detectors than NIRCAM does.

The CMB polarization Inflation Probes collectively are in an earlier stage of development than CIP is. The three proposals outline detector and instrument concepts that are extrapolations from existing experiments. As discussed in Chapter 3, CIP and EPIC-F provided the committee with more mature program plans, management approaches, and technology risk-mitigation plans. Based on the information provided to the committee, EPIC-I and CMBPol are not as far along in their technology and programmatic developments; thus, the committee was not able to adequately assess these areas.

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. The polarization, stability, and characterization of the instrument needed to achieve a successful B-mode spectrum measurement is at levels far beyond what has been reached with currently existing instruments. A successful Planck mission will go a long way but not all the way toward proving the readiness of the detector technology. Significant continued support of detector and ultracool cryocoolers (sub-100 mK) is needed to push these missions along.

The three CMB missions have proposed three different approaches for modulating the polarization signal to separate the desired polarized signal from the much larger temperature anisotropy. Given the state of development of the IP missions, it is not necessary to provide direct technology development to each of the mission teams. Investigations of different approaches for modulating the polarization signal may best be done with ground-based and balloonborne demonstrations. Although the state of CIP technology is more advanced than that of the polarization missions, it would benefit from advances in grating technologies. NASA's Astrophysics Research and Analysis Program is already in place to fund these types of investigations. However, it should be noted that the scope of the Astrophysics Research Grants Program may need to be changed to accommodate aggressive IP development.

JDEM

Science Mission Readiness Assessment Over the past decade, conclusive evidence has been assembled indicating that the expansion of the universe is accelerating. Within the standard cosmological model, this implies that some 70 percent of the energy density of the universe is in the form of a mysterious "dark energy," which counters the attractive gravitational force of matter and radiation. Little is known so far about this dark energy. Whether it is due to a cosmological constant, a dynamical evolving field, a modification of general relativity, or some other new physics cannot be determined from the data currently available. One of the goals of the Beyond Einstein Program is to provide answers to these compelling questions. Three missions to pursue these questions are being studied: the Supernova Acceleration Probe (SNAP), the Dark Energy Space Telescope (DESTINY), and the Advanced Dark Energy Physics Telescope (ADEPT). Each of the three candidate JDEM missions, described in more detail in Chapter 2, should be able to measure the time variance of dark energy at a level of precision that could have a profound impact on current understanding and would shape future research in this area. Such a result would be a major advance in basic astrophysics and cosmology and would have a broad impact across all of fundamental physics.

The goal of the JDEM missions, as presented by the report of the Dark Energy Task Force,[9] is to provide a factor-of-10 increase over the current accuracy of the dark energy ratio $w(a)$. Given that the present accuracy is around 10 percent, the JDEM missions should provide percent-level measurements of $w(a)$. Thus, the main science risk is being able to control the systematic errors to sub-percent levels. All techniques for measuring effects of dark energy will benefit greatly from both observational and theoretical studies to better understand systematic errors. If systematic errors cannot be controlled down to the sub-percent levels, the impact of JDEM could be compromised with only modest gains over ground-based studies. However, the committee believes that with substantial investment, theoretical and observational studies designed to calibrate the different distance estimators should lead to substantial progress within a few years.

Although the ultimate sensitivity of JDEM is somewhat uncertain at present, factors that will limit its sensitivity will be addressed by intermediate-term projects and by control data collected by the mission itself and by other projects. Whereas the Dark Energy Task Force projects that a JDEM mission combining at least two techniques will produce at least a factor-of-10 improvement in sensitivity over present projects, it also projects an improvement of at least a factor of 8 under worst-case assumptions regarding the ability of JDEM to control systematic errors. Even such a worst-case improvement factor would represent a critical improvement in the understanding of the nature of dark energy.

Technical Readiness Assessment Summary As described in Chapter 3, two of the three candidate missions for JDEM—DESTINY and SNAP—are relatively mature, and most of the critical technology is at TRL 5-6 or higher. The SNAP charge-coupled devices (CCDs), which are the exception, are at TRL 4-5, but there is a good plan to bring them to flight readiness. The ADEPT mission team did not provide the committee with adequate data for evaluating readiness, but in general ADEPT's critical technology has flight heritage and no major challenges.

It was stated by the ADEPT team that the mission would be based on technologies developed for missions such as Swift and GeoEye. "While there are differences, ADEPT has many similarities to the GeoEye-1 mission, which provides extensive heritage for ADEPT."[10] The mission team currently plans to use a Hawaii HgCdTe 2k × 2k infrared detector sensor. The cutoff frequency will be modified for ADEPT to 2 μm. There is some challenge to this modification, but there are ongoing programs that should demonstrate even lower cutoff frequencies. The information provided is not sufficient for the committee to perform realistic assessments of readiness, and there were insufficient data provided on the spacecraft for assessing the overall technical readiness. From the general statements made, ADEPT appears similar in complexity to the other JDEM mission candidates, with no obvious major instrument or spacecraft technical readiness challenges.

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[9] A. Albrecht et al., 2006, *Report of the Dark Energy Task Force,* Astro-ph/0609591, Batavia, Ill.: Fermi National Accelerator Laboratory.

The only identified challenges in the DESTINY technologies are in the precision pointing and stabilization, which are both recognized and being addressed by the mission team. The optics required for DESTINY are within the state of the art and can be built without any special challenge. The proposed detectors are 2k × 2k Hawaii-2RG devices. Although very similar to devices on JWST, there are differences—most notably, the cutoff wavelength. The new cutoff material has been demonstrated for the HST program, and this development will be leveraged in the DESTINY program. The information provided indicates that the DESTINY team is looking at investments required at Teledyne-Brown (the detector manufacturer) beyond those being made by JWST. The only challenge for the DESTINY spacecraft is a straightforward engineering one in the area of pointing and stabilization. Specifically, there are concerns with jitter from propellant slosh and other systematics that could present a problem for pointing repeatability. To prove out the proposed pointing and control concept, additional analysis will need to be completed to understand these issues more thoroughly. The proposed DESTINY mission concept has adequate technical margins for size, weight, power, and other non-pointing-system-related performance parameters that should provide flexibility to accommodate solutions to resolve any issues identified from the pointing performance analysis. The committee saw no major challenges to technical readiness for DESTINY.

SNAP key technologies are either mature (TRL 6 or greater) or progressing toward TRL 6 in well-planned steps. Some changes to the HgCdTe detectors' cutoff range have to be made, and these could present challenges. SNAP uses a 1.8 m composite telescope. The SNAP telescope development and primary mirror are seen as a straightforward engineering effort with no obvious challenges.

SNAP uses two types of detectors: a Lawrence Berkeley National Laboratory-supplied, radiation-hardened CCD and a Rockwell- or Raytheon-supplied mercury cadmium telluride (MCT) IR detector. The CCDs appear to be a straightforward development effort with no major challenges or problems anticipated to achieving flight readiness. MCT detectors with the required cutoff and quantum efficiency have been demonstrated under DOE funding, and the required application-specific integrated circuit has been developed for JWST. Assuming that funding can be provided in the needed time frame, these devices should not be a challenge.

The readout electronics for both detectors are claimed to be radiation-hard and to have adequate performance to meet mission objectives. The focal plane plate is about twice the size of existing devices and the material selected has extensive heritage, and no major development issues are envisioned. All components in the spectrograph are standard and should pose no development risk, with the exception of the Image Slicer. There is heritage from JWST (NIRCAM); however, if the prototype is a very close match and the testing was high fidelity with respect to SNAP requirements, there should be no major challenge to technical readiness. Finally, while most of the spacecraft bus technologies are proven and are well above TRL 6, the Ka-band transmitter is judged to be at TRL 5. With appropriate funding, this item can be brought to flight readiness in a timely manner. The SNAP mission team provided significant detail on the mission concept, showed adequate technical margins in all areas, and overall, SNAP was assessed by the committee to have no major challenges to achieving technical readiness.

LISA

Science Readiness Assessment Summary The science underlying LISA's quest to detect and use gravitational waves is at a high level of readiness, as discussed in Chapter 2. Techniques for solving Einstein's equations are sufficiently advanced to confidently predict the gravitational waves from the sources of interest and to interpret the data taken. A combination of analytical and numerical work has provided machinery to yield robust predictions from general relativity for the gravitational-wave signal from massive black hole coalescences, and these methods are now being applied to the more complex and interesting case of mergers of rapidly spinning black holes. Substantial progress is likely during the next few years, well in advance of LISA. The signals from the galactic binary sources are assumed to exist based entirely on textbook general relativity.

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[10] JDEM/ADEPT team response to the committee's Request for Information (see Appendix E in this report).

Event rates for massive black hole inspirals are uncertain by a factor of 10, while for inspirals of small objects into massive black holes, the rates are even more uncertain. These uncertainties result in a science risk factor should the mission fail to achieve its 5-year lifetime.

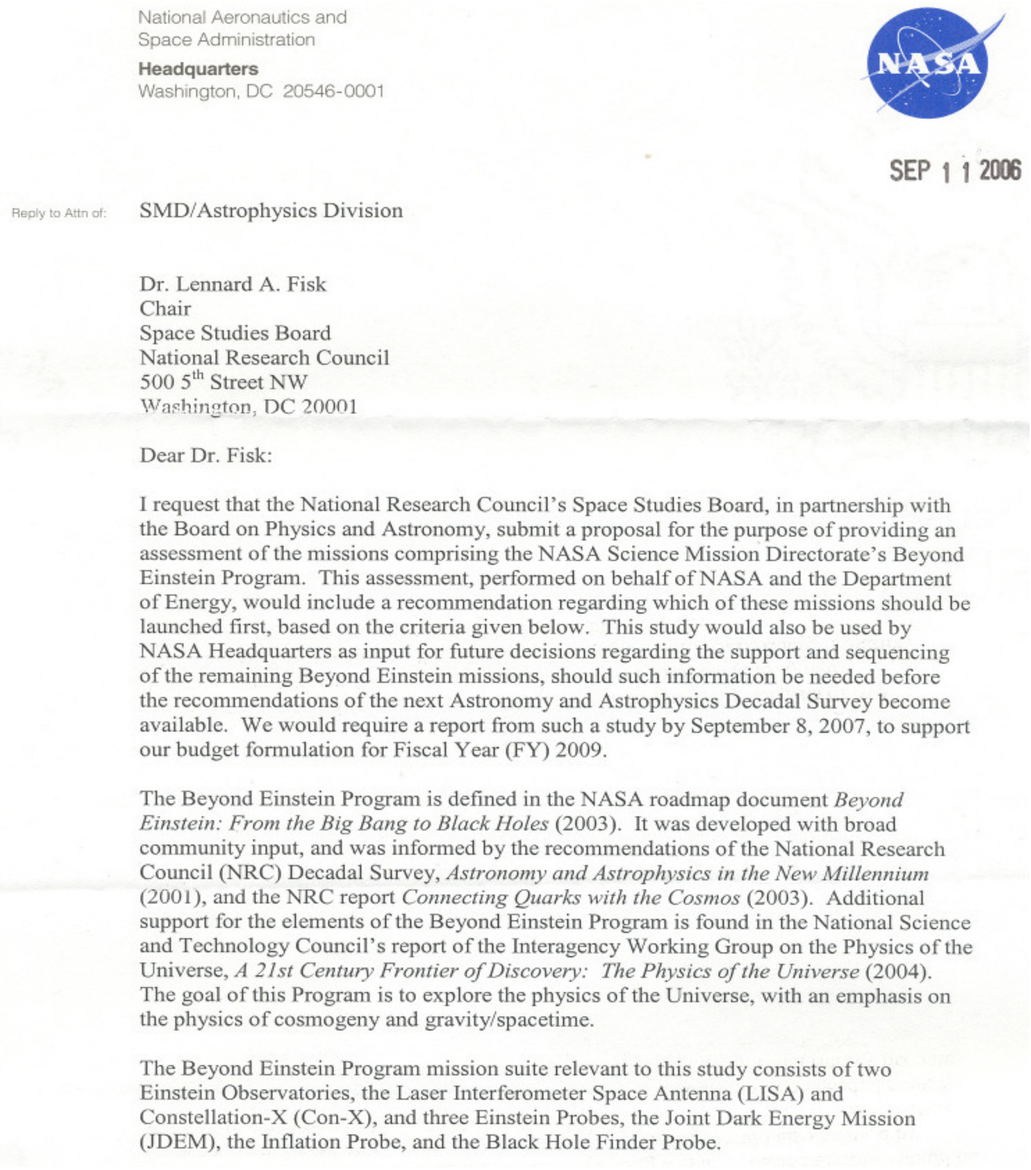
Technical Readiness Assessment Summary LISA has had considerable technology development since entering Phase A development in 2004 and has had a baseline mission architecture in place for some time. Nevertheless, a number of critical technologies and performance requirements must be developed and verified before LISA has the technical readiness to move into the implementation phase; these techniques are discussed in Chapter 3. Some of these will be tested on the ESA 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 the next highest priority for allocation of the current NASA Beyond Einstein funding wedge after the JDEM start is funding to accelerate the maturation of the technical readiness of these remaining LISA technologies. Areas that are candidates for this funding and shown at TRL levels of 4 or less and discussed in Chapter 3 include micronewton thruster technology development and lifetime tests, the point-ahead actuator, the phase measurement system, and laser frequency noise suppression.

Appendixes

A

Letter of Request



National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

SEP 11 2006

Reply to Attn of: SMD/Astrophysics Division

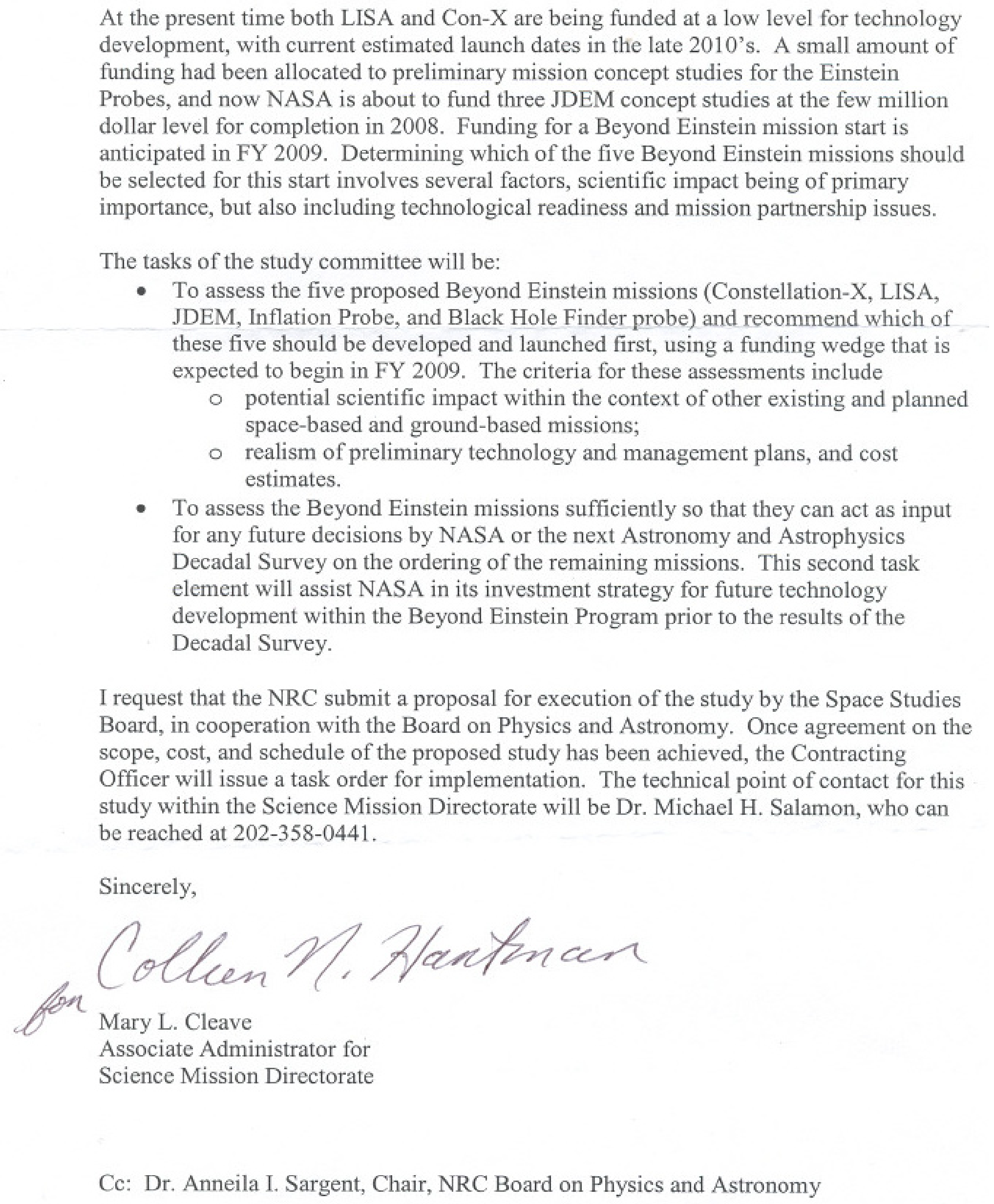
Dr. Lennard A. Fisk
Chair
Space Studies Board
National Research Council
500 5th Street NW
Washington, DC 20001

Dear Dr. Fisk:

I request that the National Research Council's Space Studies Board, in partnership with the Board on Physics and Astronomy, submit a proposal for the purpose of providing an assessment of the missions comprising the NASA Science Mission Directorate's Beyond Einstein Program. This assessment, performed on behalf of NASA and the Department of Energy, would include a recommendation regarding which of these missions should be launched first, based on the criteria given below. This study would also be used by NASA Headquarters as input for future decisions regarding the support and sequencing of the remaining Beyond Einstein missions, should such information be needed before the recommendations of the next Astronomy and Astrophysics Decadal Survey become available. We would require a report from such a study by September 8, 2007, to support our budget formulation for Fiscal Year (FY) 2009.

The Beyond Einstein Program is defined in the NASA roadmap document *Beyond Einstein: From the Big Bang to Black Holes* (2003). It was developed with broad community input, and was informed by the recommendations of the National Research Council (NRC) Decadal Survey, *Astronomy and Astrophysics in the New Millennium* (2001), and the NRC report *Connecting Quarks with the Cosmos* (2003). Additional support for the elements of the Beyond Einstein Program is found in the National Science and Technology Council's report of the Interagency Working Group on the Physics of the Universe, *A 21st Century Frontier of Discovery: The Physics of the Universe* (2004). The goal of this Program is to explore the physics of the Universe, with an emphasis on the physics of cosmogeny and gravity/spacetime.

The Beyond Einstein Program mission suite relevant to this study consists of two Einstein Observatories, the Laser Interferometer Space Antenna (LISA) and Constellation-X (Con-X), and three Einstein Probes, the Joint Dark Energy Mission (JDEM), the Inflation Probe, and the Black Hole Finder Probe.



At the present time both LISA and Con-X are being funded at a low level for technology development, with current estimated launch dates in the late 2010's. A small amount of funding had been allocated to preliminary mission concept studies for the Einstein Probes, and now NASA is about to fund three JDEM concept studies at the few million dollar level for completion in 2008. Funding for a Beyond Einstein mission start is anticipated in FY 2009. Determining which of the five Beyond Einstein missions should be selected for this start involves several factors, scientific impact being of primary importance, but also including technological readiness and mission partnership issues.

The tasks of the study committee will be:

- To assess the five proposed Beyond Einstein missions (Constellation-X, LISA, JDEM, Inflation Probe, and Black Hole Finder probe) and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include
    - potential scientific impact within the context of other existing and planned space-based and ground-based missions;
    - realism of preliminary technology and management plans, and cost estimates.
- To assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

I request that the NRC submit a proposal for execution of the study by the Space Studies Board, in cooperation with the Board on Physics and Astronomy. Once agreement on the scope, cost, and schedule of the proposed study has been achieved, the Contracting Officer will issue a task order for implementation. The technical point of contact for this study within the Science Mission Directorate will be Dr. Michael H. Salamon, who can be reached at 202-358-0441.

Sincerely,

Colleen N. Hartman
for
Mary L. Cleave
Associate Administrator for
Science Mission Directorate

Cc: Dr. Anneila I. Sargent, Chair, NRC Board on Physics and Astronomy

B

Background and Statement of Task

BACKGROUND

The National Research Council's (NRC's) 2001 astronomy and astrophysics decadal survey, *Astronomy and Astrophysics in the New Millennium*, identified a number of key scientific goals.[1] Among these were the following: to determine the large-scale properties of the universe—the amount, distribution, and nature of its matter and energy, its age, and the history of its expansion; to understand the formation and evolution of black holes; and to study the dawn of the modern universe, when the first stars and galaxies formed.

A subsequent NRC report, *Connecting Quarks with the Cosmos*,[2] identified the science connections between the fields of astronomy and astrophysics and that of fundamental physics. In 2003, building on these reports, NASA and the astronomy and astrophysics communities prepared a roadmap entitled *Beyond Einstein: From the Big Bang to Black Holes*[3] and proposed a set of five space science missions, including two Einstein Great Observatories (Constellation-X and the Laser Interferometer Space Antenna) and three Einstein Probes (Inflation Probe, the Joint Dark Energy Mission, and Black Hole Finder Probe). These missions address dark energy, black holes, gravitational radiation, properties of the cosmic microwave background radiation, and other science questions. NASA's Beyond Einstein Program also includes a technology development, theory, and education program to support the flight missions. In addition, the Department of Energy's (DOE's) Office of Science has had a growing interest in exploring questions about dark energy and dark matter, as evidenced in the NRC report *Revealing the Hidden Nature of Space and Time*.[4] DOE has sought a means for exploring dark energy and has funded research for a potential dark energy probe, and both NASA and DOE have taken steps toward a joint NASA-DOE Joint Dark Energy Mission.

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

[2] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003.

[3] 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 roadmapping effort required under the Government Performance Results Act of 1993 (Public Law No. 103-62).

[4] National Research Council, *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics*, The National Academies Press, Washington, D.C., 2006.

While the NRC has recommended the undertaking of all five of the space science missions referred to above in either *Astronomy and Astrophysics in the New Millennium* or *Connecting Quarks with the Cosmos*, the NRC has never prioritized all five missions in this suite against one another.

In response to an expected NASA "funding wedge" that is to open in fiscal year 2009, NASA and DOE requested that the NRC assess the five Beyond Einstein missions and recommend one for first launch and development. This NRC study (i.e., the present report) was to use a set of criteria, including potential scientific impact and technical readiness, to examine the five Beyond Einstein missions.

STATEMENT OF TASK

The committee will be charged to address the following tasks:

1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder Probe) and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:

   a. Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
   b. Realism of preliminary technology and management plans, and cost estimates.

2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

C

Input from the Broader Astronomy and Astrophysics Community

BEYOND EINSTEIN WEB SITE AND E-MAILS

Over the course of this study, a Web site (http://www7.nationalacademies.org/ssb/BeyondEinsteinPublic.html) was maintained to inform the science community of the charge to the Committee on NASA's Beyond Einstein Program: An Architecture for Implementation; of the committee's membership; and about its activities, including town halls and committee meeting dates. Additionally, presentations made to the committee at its meetings were made available on the Web site for general public access.

The other main feature of the Web site was the e-mail address provided (beyondeinstein@nas.edu), which the public was invited to use to make comments. These comments were shared with the committee and were posted in a special comments section of the Web site. The committee found the 23 submitted and posted comments to be insightful and useful in its deliberations.

BEYOND EINSTEIN TOWN HALLS

In an effort to engage viewpoints from the diverse astronomy and astrophysics community not represented on the committee itself, four town hall meetings were held across the country (in Newport Beach, California; Cambridge, Massachusetts; Baltimore, Maryland; and Chicago, Illinois; from February through April 2007). The full committee was divided into four groups so that there were at least 4 or 5 committee members present at each town hall. Online registration for each of these town halls allowed participants to register either as a speaker or as an observer. Speakers were encouraged to submit brief abstracts addressing the following questions:

- What are the most valuable science opportunities of the Beyond Einstein Program?
- What are the long-term goals for the science, beyond the science goals of the mission projects; are we opening a new field or resolving existing questions?
- To what degree can ground-based or existing space-based capabilities solve some of these questions?
- What is the degree of precision needed from the measurements to move the science forward?

Speakers for each town hall were chosen on the basis of the relevance of their abstracts to the questions that they were asked to address. Due to time constraints, the committee was not able to accommodate every applicant as a speaker; however, all participants, registrants, and walk-in attendees were invited to use the open-microphone period to make comments. Chosen speakers were given 5 minutes to make their oral presentations, with about 3 minutes afterward for questions from members of the committee. An open-microphone session following the speaker session allowed any person who attended the town hall to make a 2-minute statement.

The town halls were well attended, with between 15 and 23 speakers per town hall and many open-microphone participants. During each of these town halls, committee members and staff took notes that were compiled and shared with the rest of the committee. The committee found the town halls to be very informative, with many engaging and useful presentations from the participants. Following are lists of speakers and of the organizing committee members for each of the town halls.

TOWN HALL NO. 1
FEBRUARY 1, 2007
THE ISLAND HOTEL, NEWPORT BEACH, CALIFORNIA

Town Hall Speakers

Robert Cahn, Lawrence Berkeley National Laboratory
Richard Ellis, California Institute of Technology
Daniel Holz, Los Alamos National Laboratory/University of Chicago
Albert Lazzarini, California Institute of Technology
Eric Linder, University of California, Berkeley
Greg Madejski, Stanford University
Matt Malkan, University of California, Los Angeles
Harald Pfeiffer and Mark Scheel, California Institute of Technology
Katja Pottschmidt, University of California, San Diego
Alexandre Refregier, CEA Saclay
Richard Rothschild, University of California, San Diego
Michael Seiffert, Jet Propulsion Laboratory
Kip Thorne, California Institute of Technology
Brent Ware, Jet Propulsion Laboratory
Alan Weinstein, California Institute of Technology

Organizing Committee Members

Joel Primack (Chair, Town Hall No. 1), Eric Adelberger, David Bearden, Charles Kennel, Andrew Lankford, Joseph Rothenberg, Edward Wright

TOWN HALL NO. 2
FEBRUARY 12, 2007
THE ACADEMY OF ARTS AND SCIENCES, CAMBRIDGE, MASSACHUSETTS

Town Hall Speakers

Charles Baltay, Yale University
Nancy Brickhouse, Harvard-Smithsonian Center for Astrophysics
Claude Canizares, Massachusetts Institute of Technology
Bruno Coppi, Massachusetts Institute of Technology
Martin Elvis, Smithsonian Astrophysics Observatory
Enectali Figueroa-Feliciano, Massachusetts Institute of Technology
Kathryn Anne Flanagan, Massachusetts Institute of Technology
Peter Fritschel, Massachusetts Institute of Technology

Alan Guth, Massachusetts Institute of Technology
Gregory Harry, Massachusetts Institute of Technology
Julia C. Lee, Harvard University
Herman Marshall, Massachusetts Institute of Technology
Stephen S. Murray, Smithsonian Astrophysics Observatory
Michael Nowak, Massachusetts Institute of Technology
Feryal Ozel, University of Arizona
Ron Remillard, Massachusetts Institute of Technology
Natalie Roe, Lawrence Berkeley National Laboratory
David Shoemaker, Massachusetts Institute of Technology
Q. Daniel Wang, University of Massachusetts, Amherst

Organizing Committee Members

Edward Wright (Chair, Town Hall No. 2), Thomas Appelquist, James Barrowman, Mark Devlin, Lisa Randall

TOWN HALL NO. 3
MARCH 14, 2007
THE MARYLAND SCIENCE CENTER, BALTIMORE, MARYLAND

Town Hall Speakers

Kevork Abazajian, University of Maryland
Drew Baden, University of Maryland
David Band, Center for Research and Exploration in Space Science and Technology
Volker Beckmann, National Aeronautics and Space Administration/Goddard Space Flight Center
George Chartas, Pennsylvania State University
Lee Samuel Finn, Pennsylvania State University
Andrew Fruchter, Space Telescope Science Institute
Neil Gehrels, National Aeronautics and Space Administration/Goddard Space Flight Center
John P. Hughes, Rutgers University
Demosthenes Kazanas, National Aeronautics and Space Administration/Goddard Space Flight Center
Arthur Kosowsky, University of Pittsburgh
Nancy Levenson, University of Kentucky
Sean McWilliams, University of Maryland
Cole Miller, University of Maryland
John Nousek, Pennsylvania State University
Rachel Osten, University of Maryland
Andrew Ptak, Johns Hopkins University
Louis Rubbo, Pennsylvania State University
Roald Sagdeev, University of Maryland, College Park
Rita Sambruna, National Aeronautics and Space Administration/Goddard Space Flight Center
Randall Smith, Johns Hopkins University
Tracy J. Turner, University of Maryland, Baltimore County

Organizing Committee Members

Karl Gebhardt (Chair, Town Hall No. 3), William Adkins, William Gibson, Craig Sarazin, James Ulvestad

TOWN HALL NO. 4
APRIL 4, 2007
COURTYARD MARRIOTT CHICAGO DOWNTOWN, CHICAGO, ILLINOIS

Town Hall Speakers

Nahum Arav, University of Colorado
Peter Bender, JILA and the University of Colorado
Patrick Brady, University of Wisconsin-Milwaukee
Joel N. Bregman, University of Michigan
Edward Brown, Michigan State University
Megan Donahue, Michigan State University
Anne Ealet, Centre National de la Recherche Scientifique, France
Alfred Garson, Washington University in St. Louis
Dragan Huterer, University of Chicago
Stephen Kent, Fermilab
Edward W. (Rocky) Kolb, University of Chicago
Arieh Konigl, University of Chicago
Henric Krawczynski, Washington University in St. Louis
Brian McNamara, University of Waterloo
Jon Miller, University of Michigan
Stuart Mufson, Indiana University
Richard O'Shaughnessy, Northwestern University
Tod Strohmayer, National Aeronautics and Space Administration/Goddard Space Flight Center
Simon Swordy, University of Chicago
Gregory Tarle, University of Michigan
Melville Ulmer, Northwestern University
Alberto Vecchio, University of Birmingham
William Wester, Fermilab

Organizing Committee Members

Stephan Meyer (Chair, Town Hall No. 4), Joseph Fuller, Jr., Fiona Harrison, Dennis McCarthy, Clifford Will, Michael Witherell

D

List of Briefings to the Committee

MEETING 1
THE KECK CENTER OF THE NATIONAL ACADEMIES, WASHINGTON, DC
NOVEMBER 6-8, 2006

November 6, 2006

NASA Presentation to the NRC Beyond Einstein Program Assessment Committee. Rick Howard, Acting Director, Astrophysics Division, Science Mission Directorate, NASA Headquarters

OSTP Perspectives. Rob Dimeo, Office of Science and Technology Policy (OSTP)

Congressional Perspective. Dixon Butler, House Appropriations Committee staff

From Quarks to the Cosmos to the BEPAC [the Committee on NASA's Beyond Einstein Program: An Architecture for Implementation]. Michael S. Turner, Kavli Institute for Cosmological Physics of the University of Chicago and former chair of the NRC Committee on the Physics of the Universe

What Is the Nature of Dark Energy? Joseph Lykken, Fermi National Accelerator Laboratory

The Cosmic Microwave Background and the Dawn of Time. Marc Kamionkowski, California Institute of Technology

Did Einstein Have the Last Word on Gravity?—Gravitational Waves, A Unique and Powerful Channel for Studying Strong Gravity Systems. Scott A. Hughes, Massachusetts Institute of Technology

Did Einstein Have the Last Word on Gravity?—X-ray Studies of Black Holes. Chris Reynolds, Department of Astronomy, University of Maryland

November 7, 2006

LISA: The Laser Interferometer Space Antenna. Craig Hogan, University of Washington, and Karsten Danzmann, Albert Einstein Institute/Max Planck Institute for Gravitational Physics and Leibniz Universität Hannover

The Constellation X-ray Mission. Nicholas White, NASA Goddard Space Flight Center (GSFC), and Harvey Tananbaum, Smithsonian Astrophysical Observatory (SAO)

EXIST Concept for BHFP: Hard X-ray Black Hole Surveys in Space and Time. Josh Grindlay, Harvard University

The Coded Aperture Survey Telescope for Energetic Radiation: A Candidate Concept for the Black Hole Finder Probe. Mark McConnell, University of New Hampshire
The SNAP Experiment. Michael Levi, SNAP Project Director, co-Principal Investigator, Lawrence Berkeley National Laboratory (LBNL)
DESTINY: Dark Energy Space Telescope. Tod Lauer, National Optical Astronomy Observatory (NOAO)
JDEM: An ADEPT Approach. Chuck Bennett, Johns Hopkins University
The Einstein Polarization Interferometer for Cosmology (EPIC). Peter Timbie, University of Wisconsin, Madison
Experimental Probe of Inflationary Cosmology (EPIC). Jamie Bock, Jet Propulsion Laboratory (JPL)/California Institute of Technology
Probing Inflation with CMBPol. Gary Hinshaw, NASA/GSFC
CIP: Cosmic Inflation Probe. Gary Melnick, SAO

MEETING 2
THE ISLAND HOTEL, NEWPORT BEACH, CALIFORNIA
JANUARY 30-FEBRUARY 1, 2007

January 30, 2007

DESTINY: Dark Energy Space Telescope. Tod Lauer, NOAO
Advanced Dark Energy Physics Telescope (ADEPT). Warren Moos, Johns Hopkins University, and Daniel Eisenstein, University of Arizona
SNAP. Saul Perlmutter, LBNL/University of California, Berkeley, and Michael Levi, LBNL/University of California, Berkeley
CASTER: A Candidate Concept for the Black Hole Finder Probe. Mark McConnell, University of New Hampshire
EXIST Concept for BHFP: Highlights from Response to RFI. Josh Grindlay, Harvard University; Paolo Coppi, Yale University; and Scott Barthelmy, NASA/GSFC
CIP: Cosmic Inflation Probe. Gary Melnick, SAO
Probing Inflation with CMBPol. Gary Hinshaw, NASA/GSFC
Experimental Probe of Inflationary Cosmology (EPIC). Jamie Bock, JPL/California Institute of Technology
The Einstein Polarization Interferometer for Cosmology (EPIC). Peter Timbie, University of Wisconsin, Madison
LISA. Robin Stebbins, NASA/GSFC; Nick Jedrich, NASA/GSFC; Mansour Ahmed, NASA/GSFC; Alberto Gianolio, European Space Agency (ESA)/European Space Research and Technology Centre
Constellation-X. Ann Hornschemeier, NASA/GSFC; Jay Bookbinder, SAO; Jean Grady, NASA/GSFC; Harvey Tananbaum, SAO; Nicholas White, NASA/GSFC

January 31, 2007

Gamma Ray Bursts and the Transient High Energy Sky. Chryssa Kouveliotou, NASA Marshall Space Flight Center
Cosmic Feedback and the Growth of Structure. Mitch Begelman, University of Colorado
Probing Cosmology with X-ray Clusters. Steve Allen, Stanford University

MEETING 3
COURTYARD MARRIOTT CHICAGO DOWNTOWN, CHICAGO, ILLINOIS
APRIL 5-7, 2007

April 5, 2007

LISA and LISA Pathfinder. David Southwood, ESA

April 6, 2007

Source of Error in Dark Energy Measures. Gary Bernstein, University of Pennsylvania

E

Request for Information to Mission Teams

The instructions and questions contained in the Request for Information (RFI) reproduced in this appendix were sent to the Beyond Einstein Program candidate mission teams for additional input to the Committee on NASA's Beyond Einstein Program. Questions requesting further clarification were sent at later dates to individual mission teams, based on their responses to this RFI.

Instructions for Responding

The committee requests that mission teams respond to the following questions as completely as possible. However, we fully recognize that the missions are at different stages of definition, and answers may not be available for many of the more detailed questions. For example, a specific spacecraft implementation may not have been selected, and so many details cannot be provided. In this case it is sufficient for the committee to understand the overall spacecraft complexity and requirements. We have attempted to indicate below where details are optional.

We also request that you please ensure that any written responses or diagrams that you include do not include ITAR-controlled information. The NRC will consider your response as public information and available to the public, if requested.

SCIENCE AND INSTRUMENTATION

Please answer the following as completely as possible:

Describe the scientific objectives and the measurements required to fulfill these objectives.

Describe the technical implementation you have selected, and how it performs the required measurements.

Of the required measurements, which are the most demanding? Why?

Present the performance requirements (e.g., spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science measurements.

Describe the proposed science instrumentation, and briefly state the rationale for its selection.

For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a key requirement, what will the impact be on achievement of your science objectives?

Indicate the technical maturity level of the major elements of the proposed instrumentation, along with the rationale for the assessment (i.e., examples of flight heritage, existence of breadboards, prototypes, etc.).

Briefly describe the overall complexity level of instrument operations, and the data type (e.g., bits, images) and estimate of the total volume returned.

If you have identified any descope options that could provide significant cost savings, describe them, and at what level they put performance requirements and associated science objectives at risk.

In the area of science and instrumentation, what are the three primary technical issues or risks?

Fill in entries in the Instrument Table to the extent possible. If you have allocated contingency, please include as indicated; if not, provide just the current best estimate (CBE).

Optional details—If you have answers to the following detailed questions, please provide:

For the science instrumentation, describe any concept, feasibility, or definition studies already performed (to respond you may provide copies of concept study reports, technology implementation plans, etc.).

For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes.

Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation.

Provide an instrument development schedule if available.

Provide a schedule and plans for addressing any required technology developments, and the associated risks.

Describe the complexity of the instrument flight software, including an estimate of the number of lines of code.

Compare the scientific reach of your mission with that of other planned space- and ground-based missions.

Instrument Table

Item	Value/Description	Units
Number and type of instruments		
Number of channels		
Size/dimensions (for each instrument)		m × m × m
Payload mass with contingency		kg, %
Average payload power with contingency		W, %
Average science data rate with contingency		kbps, %
Instrument fields of view (if appropriate)		
Pointing requirements (knowledge, control, stability)		Deg, deg/s

MISSION DESIGN

Please answer the following as completely as possible:

- Provide a brief descriptive overview of the mission design (launch, orbit, pointing strategy) and how it achieves the science requirements (e.g., if you need to cover the entire sky, how is it achieved?).
- Provide entries in the mission design table to the extent possible. Those entries in italics are optional. For mass and power, provide contingency if it has been allocated; if not, provide just your current best estimate (CBE). To calculate margin, take the difference between the maximum possible value (e.g., launch vehicle capability) and the maximum expected value (CBE plus contingency).
- Provide diagrams or drawings (if you have them) showing the observatory (payload and S/C) with the components labeled and a descriptive caption. If you have a diagram of the observatory in the launch vehicle fairing indicating clearance, please provide it.
- Overall (including science, mission, instrument and S/C), what are the three primary risks?

Optional detail (provide if available):

- If you have investigated a range of possible launch options, describe them, as well as the range of acceptable orbit parameters.
- If you have identified key mission trade-offs and options to be investigated, describe them.

Mission Design Table

Parameter	Value	Units
Orbit parameters (apogee, perigee, inclination, etc.)		
Mission lifetime		mos
Maximum eclipse period		min
Spacecraft dry bus mass and contingency		kg, %
Spacecraft propellant mass and contingency		kg, %
Launch vehicle		
Launch vehicle mass margin		kg, %
Spacecraft bus power and contingency by subsystem		W, %
Mass weighted reuse percentage of payload and spacecraft subsystem components		%
Mass weighted redundancy of payload and spacecraft subsystem components		

SPACECRAFT IMPLEMENTATION

Please answer the following as completely as possible:

- Describe the spacecraft characteristics and requirements. Include, if available, a preliminary description of the spacecraft design and a summary of the estimated performance of the spacecraft.
- Provide an overall assessment of the technical maturity of the subsystems and critical components. In particular, identify any required new technologies or developments or open implementation issues.
- What are the three greatest risks with the S/C?

Optional detail (provide if you have selected a specific S/C implementation):

- If you have required new S/C technologies, developments, or open issues and you have identified plans to address them, please describe (to answer you may provide technology implementation plan reports or concept study reports).
- Describe subsystem characteristics and requirements to the extent possible. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins.
- Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing instrumentation or design/flight heritage. Discuss the steps needed for space qualification.
- Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e., jitter/momentum considerations, thermal environment/temperature limits, etc.).
- Define the Technology Readiness Level of critical S/C items along with a rationale for the assigned rating.
- Provide a preliminary schedule for the spacecraft development.

Spacecraft Characteristics Table
(Optional—fill out any known entries if you have selected an implementation.)

Spacecraft Bus	Value/Summary, Units
Structure	
Structures material (aluminum, exotic, composite, etc.)	
Number of articulated structures	
Number of deployed structures	
Thermal Control	
Type of thermal control used	
Propulsion	
Estimated Delta-V budget, m/s	
Propulsion type(s) and associated propellant(s)/oxidizer(s)	
Number of thrusters and tanks	
Specific impulse of each propulsion mode, seconds	
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	
Attitude control capability, degrees	
Attitude knowledge limit, degrees	
Agility requirements (maneuvers, scanning, etc.)	
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	
Command and Data Handling	
Spacecraft housekeeping data rate, kbps	
Data storage capacity, Mbits	
Maximum storage record rate, kbps	
Maximum storage playback rate, kbps	
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	
Array size, meters × meters	
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	
On-orbit average power consumption, watts	
Battery type (NiCd, NiH, Li-ion)	
Battery storage capacity, amp-hours	

MISSION OPERATIONS

- Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc.). Analogies with currently operating or recent missions are helpful.
- Identify any unusual constraints or special communications, tracking, or near-real-time ground support requirements.
- Identify any unusual or especially challenging operational constraints (i.e., viewing or pointing requirements).

Mission Operations and Ground Data Systems Table
(Optional—provide only if you have selected an S/C and operations implementation.)

Downlink Information	**Value, Units**
Number of data dumps per day	
Downlink frequency band, GHz	
Telemetry data rate(s), bps	
S/C transmitting antenna type(s) and gain(s), DBi	
Spacecraft transmitter peak power, watts	
Downlink receiving antenna gain, DBi	
Transmitting power amplifier output, watts	
Uplink Information	**Value, Units**
Number of uplinks per day	
Uplink frequency band, GHz	
Telecommand data rate, bps	
S/C receiving antenna type(s) and gain(s), DBi	

TOTAL MISSION COST FUNDING PROFILE TEMPLATE

(FY costs[a] in Real-Year Dollars, Totals in Real-Year and 2007 Dollars)

Item	FY1	FY2	FY3	FY4	FY5	...	FYn	Total (Real Yr.)	Total (FY 2007)
Cost									
Concept study									
Science									
Instrument A									
Instrument B									
Spacecraft									
Ground data system development									
MSI&T[b]									
Launch services									
MO&DA[c]									
Education/outreach									
Reserves									
Other (specify)									
Total cost	$	$	$	$	$	$	$	$	$
Contributions									
Concept study									
Science									
Instrument A									
Instrument B									
Spacecraft									
Ground data system development									
MSI&T[b]									
Launch services									
MO&DA[c]									
Education/outreach									
Reserves									
Other (specify)									
Total contributions	$	$	$	$	$	$	$	$	$
						Total mission cost			$

[a] Costs should include all costs including any fee.
[b] MSI&T, Mission System Integration and Test and preparation for operations.
[c] MO&DA, Mission Operations and Data Analysis.

F

Mission Teams' Technology Funding Inputs to the Committee

The funding requirements and assumptions for continuing the mission development activities for the 11 mission candidates shown in Table F.1 were essentially developed from inputs provided to the committee by the individual mission teams. As shown, the teams were asked to identify continuation activities at two budgetary levels: (1) the level of mission risk reduction to prepare input for the next astronomy and astrophysics decadal survey of the National Research Council and (2) the bare minimum budget level to sustain the mission team in a meaningful way.

TABLE F.1 NASA Investment Options for 11 Beyond Einstein Candidate Missions

		Assessment of Mission Team Requirements: Fully Prepare for the Astronomy and Astrophysics Decadal Survey[a]			Assessment of Bare Minimum: Team Sustainment Level[a]		
Mission Area[a]	Mission	FY 2008	FY 2009	FY 2010	FY 2008	FY 2009	FY 2010
Inflation Probes	CMBPol[b,c,d]						
	EPIC-F[b,c,e]	$300,000	$300,000	$300,000	$300,000	$300,000	$300,000
	EPIC-I[b,c,f]	$250,000	$250,000	$250,000	<$250,000	<$250,000	<$250,000
	Without APRA funding	$750,000	$750,000	$750,000	<$750,000	<$750,000	<$750,000
	CIP[g]	$870,000	$840,000	$682,000	<<$875,000	<<$875,000	<<$875,000
	Cross-mission CMB detector flight—packaging[b,c]	$2 million	$2 million	$2 million	$2 million	$2 million	$2 million
BHFP	CASTER	$740,000	$740,000	$740,000	$150,000	$150,000	$150,000
	Balloon Flight in Phase A[h]	$240,000	$240,000	$240,000	$150,000	$150,000	$150,000
	EXIST[i]	$200,000	$1.8 million	$1.8 million	$100,000	$600,000	$600,000
Con-X	Con-X[j]	$10 million	$10 million	$10 million	$6.2 million	$6.2 million	$6.2 million
JDEM	ADEPT	$2.3 million	$2.3 million	$2.3 million	$0.9 million	$0.9 million	$0.9 million
	SNAP[k]	$3.0 million	$3.0 million	$3.0 million	$3.0 million	$3.0 million	$3.0 million
	DESTINY	$1 million	$1 million	$1 million	$1 million	$1 million	$1 million
LISA	LISA[l]	$6 million	$6 million	$6 million	$6 million	$6 million	$6 million

NOTE: Acronyms are defined in Appendix G.

[a] Does not include civil service or Jet Propulsion Laboratory costs.

[b] Investment in detectors and focused detector integration into large-scale flight-ready arrays.

[c] Assumes additional ongoing NASA, DOE, NIST funding of an additional $2 million per year for development of bolometric array technology continues.

[d] No data provided to the committee from the mission team.

[e] Assumes team is successful in proposed funding for a balloon experiment "SPIDER" to demonstrate instrument, six detectors, wave plate, and telescope concept.

[f] Assumes team is successful in proposed NASA Astronomy and Physics Research Analysis (APRA) Program funding for a balloon flight demonstration of a scalable millimeter-wave bolometric interferometer at $1,549,513 over the period from the second quarter of FY 2008 through the second quarter of FY 2011.

[g] Assumes successful JWST detector demonstration.

[h] Assumes team is successful in proposed funding for a balloon experiment under NASA's APRA Program or it is deferred to Phase A.

[i] Assumes $600,000 APRA Program proposal for LET development is successful and current HET APRA funding is maintained through March 2009.

[j] Constellation-X input scaled back from the team's input that was proposed as needed for a new start to a level assessed by the committee that would allow the team to prepare for the 2010 astronomy and astrophysics decadal survey.

[k] Currently there is $3 million per year in DOE funding for SNAP.

[l] Excludes ESA funding and NASA ROSES research grant funding.

G

Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
ACS	attitude control system
ACT	Advanced Compton Telescope
AD&C	attitude determination and control
ADEPT	Advanced Dark Energy Physics Telescope
ADR	Adiabatic Demagnetization Refrigerator
AL	arm locking
ALMA	Atacama Large Millimeter Array
ASCA	Advanced Satellite for Cosmology and Astrophysics
ASIC	application-specific integrated circuit
ATT	advanced technology testbed
AU	astronomical unit
BAO	baryon acoustic oscillation
BAT	Burst Alert Telescope
BE	Beyond Einstein
BH	black hole
BHFP	Black Hole Finder Probe
BICEP	Background Imaging of Cosmic Extragalactic Polarization
CASTER	Coded Aperture Survey Telescope for Energetic Radiation
CC	continuous clocking
CCD	charge-coupled device
CGRO	Compton Gamma Ray Observatory
CIP	Cosmic Inflation Probe
CL	galaxy cluster
CLIC	column loading input chip
CMB	cosmic microwave background
CMBPol	Cosmic Microwave Background Polarimeter
CMT	Colloid Micronewton Thruster
COBE	Cosmic Background Explorer
CoBRA	complexity-based risk assessment
Con-X	Constellation-X

COSMOS	Cosmological Evolution Survey
Cs-FEEP	Cesium Field Emission Electric Propulsion
CsI	cesium iode
CTE	coefficient of thermal expansion
CZT	cadmium-zinc-telluride
DDT&E	design, development, test, and evaluation
DE	dark energy
delta-v	incremental change in velocity
DEP	Dark Energy Probe
DES	Dark Energy Survey
DESTINY	Dark Energy Space Telescope
DETF	Dark Energy Task Force
DOD	Department of Defense
DoD	degree of difficulty
DOE	Department of Energy
DRS	disturbance-reduction system
EELV	evolved expendable launch vehicle
ELV	expendable launch vehicle
EM	engineering model
EMRI	extreme mass-ratio inspiral
EOL	end of life
EPIC-F	Experimental Probe of Inflationary Cosmology
EPIC-I	Einstein Polarization Interferometer for Cosmology
eROSITA	extended Roentgen Survey with an Imaging Telescope Array
ESA	European Space Agency
EXIST	Energetic X-ray Imaging Survey Telescope
FEEP	Field Emission Electric Propulsion
FGS	fine guidance sensor
FMA	flight mirror assembly
FOBAS	Fast On-board Burst Alert System
FOV	field of view
FPA	focal plane array
FPGA	field programmable gate array
GBT	Green Bank Telescope
GLAST	Gamma-ray Large Area Space Telescope
GPB	Gravity Probe B
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRB	gamma-ray burst
GRO	Gamma Ray Observatory
GRS	Gravitational Reference Sensor
GSFC	Goddard Space Flight Center
HDF	Hubble Deep Field
HEFT	High Energy Focusing Telescope
HEI	High Energy Imager
HEPAP	High Energy Physics Advisory Panel
HERO	High-Energy Replicated Optics
HET	High Energy Telescope
HHT	Heinrich Hertz Telescope
HST	Hubble Space Telescope

HUDF	Hubble Ultra-Deep Field
HXT	Hard X-ray Telescope
IMBH	intermediate-mass black hole
IMU	inertial measurement unit
In-FEEP	Indium Needle Field Emission Electric Propulsion
InFOCUS	International Focusing Optics Collaboration for micro-Crab Sensitivity
IP	Inflation Probe
IR	infrared
IRAS	Infrared Astronomical Satellite
IS	Image Slicer
ISO	Infrared Space Observatory
ITAR	International Traffic in Arms Regulations
JDEM	Joint Dark Energy Mission
JFET	junction gate field-effect transistor
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
L2	Lagrange Point 2
$LaBr_3$	lanthanum bromide
LAGEOS	Laser Geodynamics Satellites
LBNL	Lawrence Berkeley National Laboratory
LCC	life-cycle cost
LEI	Low Energy Imager
LEO	low Earth orbit
LET	Low Energy Telescope
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LM	Lockheed Martin
LOFAR	Low Frequency Array
LP	LISA Pathfinder
LSS	Large-Scale Structure
LSST	Large Synoptic Survey Telescope
LST	Large Survey Telescope
LSU	Louisiana State University
LV	launch vehicle
MBI	main beam interference
MCT	mercury cadmium telluride
MEMS	microelectromechanical system
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging (mission)
MIRI	mid-infrared instrument
MO&DA	mission operations and data analysis
MSFC	Marshall Space Flight Center
MWA	Mileura Wide-Field Array
NAFCOM	NASA Air Force Cost Model
NASA	National Aeronautics and Space Administration
NeXT	New X-ray Telescope
NFIRE	Near Field Infrared Experiment
NIR	near-infrared
NIRCAM	Near-Infrared Camera
NIRSpec	Near-Infrared Spectrometer
NRC	National Research Council

NSF	National Science Foundation
NTD	neutron transmutation doped
OSTP	Office of Science and Technology Policy
PDR	preliminary design review
PMS	phase measurement system
PMT	photo-multiplier tube
PS	pre-stabilization
QE	quantum efficiency
R&D	research and development
RFI	request for information
ROSAT	Röntgensatellit
ROSES	Research Opportunities in Space and Earth Sciences
SAA	South Atlantic Anomoly
SAIC	Science Applications International Corporation
SAO	Smithsonian Astrophysical Observatory
SBIR	Small Business Innovation Research
SCUBA	Sub-millimeter Common User Bolometer Array
SDSS	Sloan Digital Sky Survey
SEUS	Structure and Evolution of the Universe Subcommittee
SKA	Square Kilometer Array
SMBH	supermassive black hole
SN	supernova
SNAP	Supernova Acceleration Probe
SQUID	Superconducting Quantum Interference Device
SSAC	Space Science Advisory Committee
SwRI	Southwest Research Institute
SXT	Spectroscopic X-ray Telescope
TDI	time-delayed interferometry
TE	timed exposure
TES	transition edge sensor
TMA	three mirror astigmatic
TPF	Terrestrial Planet Finder
TRDSS	Tracking and Data Relay Satellite System
TRL	Technology Readiness Level
ULE	ultralow expansion
ULX	ultraluminous x-ray source
VLT	Very Large Telescope
VPM	variable-delay polarization modulator
WFC	wide-field camera
WHIM	Warm-Hot Intergalactic Medium
WISE	Wide-field Infrared Survey Explorer
WL	weak lensing
WMAP	Wilkinson Microwave Anisotropy Probe
XEUS	X-ray Evolving Universe Spectroscopy
XGS	X-ray Grating Spectrometer
XMM-Newton	X-ray Multi-Mirror Mission-Newton
XMS	X-ray Microcalorimeter Spectrometer
XQC	X-ray Quantum Calorimeter
XRS	X-ray Spectrograph
XSS-11	Experimental Satellite System-11

H

Glossary

accretion, accretion disks: The process by which gas flows around and onto a compact gravitating object. Astronomical objects as diverse as protostars and active galaxies may derive their power from the gravitational energy released by the infall, or accretion, of material onto a central object. The combined effects of gravity and rotation often force the accreting material into an orbiting accretion disk.

active galactic nucleus (AGN): Energetic phenomena in the nuclei, or central regions, or galaxies that cannot be attributed clearly and directly to stars.

Advanced Satellite for Cosmology and Astrophysics (ASCA): Japan's fourth cosmic x-ray astronomy mission, and the second mission for which the United States provided part of the scientific payload. It is the first satellite to use charge-coupled devices for x-ray astronomy, and its primary goal is the x-ray spectroscopy of astrophysical plasmas—especially the analysis of discrete features such as emission lines and absorption edges. It was formerly named Astro-D.

angular diameter: The diameter of an object as measured as an angle.

angular resolution: The resolving power of an optical device such as a telescope.

anisotropy: Dependence of the properties of a system on the orientation or the direction of observation. The distribution of galaxies in space is not uniform, whereas the intensity of the *cosmic background radiation* from the *big bang* is highly uniform in all directions—that is, it is almost isotropic. Astronomers are using sensitive telescopes to study the small anisotropies in the cosmic background radiation that led to the present nonuniform distribution of galaxies.

antimatter: Matter composed of antiparticles (e.g., antiprotons, antineutrons, antielectrons) instead of particles (e.g., protons, neutrons, electrons).

antiparticle: Counterpart to a particle, with properties identical to those of the particle, except that the antiparticle's electrical charge and a few other properties are opposite those of the particle. When a particle and its antiparticle meet, they can annihilate each other and release energy. In the Standard Model of Particle Physics, antiparticles are natural analogues to all the particles.

arcminute: A unit of angle corresponding to 1/60th of a degree. The full Moon is 30 arcminutes in diameter.

arcsecond: A unit of angle corresponding to 1/3600th of a degree; 1/60th of an *arcminute*. An arcsecond is approximately the size of a dime viewed from a distance of 1 mile.

array: There are two examples of arrays in common use in astronomy: (1) a group, or array, of telescopes combined to simulate a single large telescope, kilometers or even thousands of kilometers across; (2) astronomical instruments composed of detector arrays or charge-coupled devices that consist of thousands of individual detectors constructed on centimeter-sized wafers of silicon, or other materials.

astronomical unit (AU): The mean distance between Earth and the Sun.

Atacama Large Millimeter Array (ALMA): A single research instrument composed of up to 80 high-precision antennas that will enable research into optically dark regions by probing the millimeter portion of the electromagnetic spectrum, where the cold universe shines brightly. ALMA is designed to probe the first stars and galaxies and directly image the formation of planets.

baryon: A subatomic particle with mass and three constituent quarks bound together by the strong force, such as a proton or neutron. Ordinary matter as we know it consists largely of baryons.

baryon acoustic oscillations: Cosmological perturbations in the early universe excited sound waves in the photon-baryon fluid. These baryon acoustic oscillations define a standard ruler whose length is the distance that sound can travel, at a speed of $\sim c/\sqrt{3}$, before decoupling.

big bang: The theory that the universe began with all matter and energy concentrated to very high density and temperature some 13 billion years ago. The present universe expanded from that era and is still expanding.

black hole: A region of space in which the gravitational pull is so strong that, classically, nothing can escape. The boundary of this region is called the black hole's event horizon. Black holes can form when a massive star undergoes gravitational collapse.

blazar: Believed to be an active galactic nucleus (AGN) that has one of its relativistic jets pointed toward Earth, so that the emission we observe is dominated by phenomena occurring in the jet region. Among all AGNs, blazars emit over the widest range of frequencies and are detected from radio to gamma ray.

B-mode polarization: A kind of polarization of radiation that is primarily vortex-like and is theorized to be predominantly produced during the inflation period.

boson star: A star composed of self-gravitating nonbaryonic matter called bosons. All fundamental particles in nature can be divided into one of two categories: fermions or bosons. Bosons, unlike fermions, do not obey the Pauli exclusion principle. While examples of fermions include electrons, protons, neutrons, quarks, and neutrinos, particles classified as bosons include photons and gluons.

brown dwarf: A star-like object that contains less than about 0.08 the mass of the Sun and is thus too small to ignite nuclear fuels and become a normal star. Brown dwarfs emit small amounts of infrared radiation owing to the slow release of gravitational energy and may be a component of dark matter.

Chandra X-ray Observatory: A satellite designed to observe x-rays from high-energy regions of the universe, such as the remnants of exploded stars, black holes, supernovas, and dark matter and to increase the understanding of the origin, evolution, and destiny of the universe. It was launched and deployed by Space Shuttle Columbia on July 23, 1999.

charge-coupled device (CCD): An electronic image detector used in modern video cameras and astronomical instruments that uses semiconductor technology to detect incident radiation.

comet coma: A cloud, formed as the ice around the comet nucleus evaporates, around the central part of the comet. This cloud, the atmosphere of the comet, can extend for millions of miles.

Compton Gamma Ray Observatory (CGRO): The second of NASA's Great Observatories, launched April 5, 1991. Its mission is to study the high-energy universe, including solar flares, gamma-ray bursts, pulsars, nova and supernova explosions, accreting black holes of stellar mass, quasar emission, and interactions of cosmic rays with the interstellar medium.

Cosmic Background Explorer (COBE): A satellite launched in November 1989, it made precision measurements of the spectrum of the microwave background radiation and discovered tiny variations in its intensity across the sky that arose due to small variants in the density of matter.

cosmic microwave background (CMB) radiation: The residual light from the big bang. Although the CMB is nearly uniform, there are tiny fluctuations in its temperature owing to variations in the density of the early universe. Some of these tiny fluctuations grew to form galaxies.

cosmic nucleosynthesis: Fusion in the early universe when it was very dense and very hot. This fusion of lighter elements resulted in the creation of heavier elements such as deuterium. Cosmic nucleosynthesis is to be compared to stellar nucleosynthesis, which refers to the formation of heavier elements within stars during their fusion life cycles.

cosmic rays: Protons, nuclei of heavy atoms, and possibly other particles that have been acclerated to high energies by astrophysical processes in the universe and that impinge on Earth.

cosmic string: Theoretical string-like concentrations of matter that could explain the youngest structures seen in the universe. The idea of a cosmic string is based on the idea of boundaries between crystals that form in solidifying liquids.

Cosmic Visions 2025: The European Space Agency's plan for space science until 2025.

cosmography: The study and description or mapping of the universe.

cosmological constant Λ: The energy density associated with the vacuum (empty space). Recent astronomical observations suggest that there is a net energy associated with the vacuum. If there is a positive vacuum energy, then the expansion of the universe will eventually accelerate and our descendants will find themselves in a nearly empty universe.

dark current: The electric current that flows through a detector when it is activated but not receiving any light.

dark energy: An as-yet-unknown form of energy that pervades the universe. Its presence was inferred from the discovery that the expansion of the universe is accelerating, and these observations suggest that about 70 percent of the total density of matter plus energy is in this form. One explanation for dark energy is Einstein's cosmological constant.

Dark Energy Survey (DES): A survey to be conducted over the course of 5 years using an extremely red-sensitive 500 megapixel camera mounted on a 2-meter telescope. Proposed by Fermilab in 2004, the project would study the nature of dark energy.

Dark Energy Task Force (DETF): A subcommittee of the Astronomy and Astrophysics Advisory Committee chartered to advise NASA, the National Science Foundation, and the Department of Energy on the future of dark energy research.

dark matter: Matter that does not emit enough light or other electromagnetic radiation to be observed directly. Most of the matter in the universe is dark. Cold dark matter is made of particles (e.g., axions or neutralinos) that move slowly compared with the speed of light; hot dark matter is made of particles (e.g., neutrinos) that move at nearly the speed of light.

Deep Space Network (DSN): International network of antennas that support interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe.

Eddington limit: The upper limit of a star's electromagnetic radiation pressure, determined by the limitation that its electromagnetic pressure cannot exceed the force of gravity holding the star together.

Einstein Great Observatories: A classification by NASA in its line of astrophysics-based satellites, these are designed to be facility-class missions that can accomplish a broad range of science goals. Laser Interferometer Space Antenna and Constellation-X are Einstein Great Observatories.

Einstein X-ray Observatory: Launched in November 1978, it was the first fully imaging x-ray telescope in space, with the specific purpose of enabling x-ray astronomy research. It was also called the High Energy Astrophysics Observatory (HEAO)-2. Its mission ended in April 1981.

E-mode: A kind of polarization pattern that can be produced both during inflation and at later times by electron scattering.

extended Roentgen Survey with an Imaging Telescope Array (eROSITA): A telescope that will perform the first imaging all-sky survey of medium x-rays, up to 10 keV.

facility-class observatory: In addition to its key science projects, a facility-class observatory is meant to contribute to many other astronomical areas based on observations proposed by general observers.

flare: See *solar flare*.

frame dragging: An effect predicted by Einstein's general theory of relativity such that the rotation of an object (such as Earth) twists local spacetime around that object.

galaxy: An isolated grouping of tens to hundreds of billions of stars ranging in size from 5,000 to 150,000 light-years across. Spiral galaxies such as our own *Milky Way* are flattened disks of stars and often contain large amounts of gas out of which new stars can form. Elliptical galaxies are shaped more like footballs and are usually devoid of significant quantities of gas.

galaxy clusters: Groups of hundreds or thousands of galaxies. The nearest galaxy cluster is the *Virgo cluster*.

gamma-ray burst: Bursts of gamma rays from cosmic sources observed by detectors on satellites. Several hundred are detected per year. They range in duration from fractions of a second to several seconds. Most gamma-ray bursts come from objects at cosmological distances.

Gamma-ray Large Area Space Telescope (GLAST): A next-generation high-energy gamma-ray observatory designed for making observations of celestial gamma-ray sources in the energy band extending from 10 MeV to more than 100 GeV. GLAST is a joint project between NASA, the U.S. Department of Energy, and institutions in France, Germany, Japan, Italy, and Sweden. It is scheduled to launch in late 2007.

gas mass fraction: The fraction of material (e.g., in a galaxy) composed of gas, according to mass.

general theory of relativity: Einstein's theory of gravity in which gravity arises from the curved geometry of space and time.

gluon: The exchange particles for the strong (or color) force between quarks. As exchange particles, the gluon's role is analogous to the photon's role in the electromagnetic force between two charged particles.

gravitational lens: An object in which rays of light from a distant astronomical source are deflected by the gravitational pull of an intermediate mass that may be a galaxy or a cluster of galaxies. The deflection causes a distortion in the image of the distant source and sometimes also leads to multiple images.

gravitational wave: A traveling perturbation in the gravitational field. As small bodies spiral into massive black holes, they trace tens of thousands of orbits, and emit waves that encode the details of the spacetime structure around the massive black hole.

graviton: The putative quantum particle of gravity.

Gravity Probe B (GPB): A relativity gyroscope experiment launched in 2004. It was developed by NASA and Stanford University to test unverified predictions of Einstein's general theory of relativity by measuring how space and time are warped by Earth and the effect of *frame dragging*.

Gravity Recovery and Climate Experiment (GRACE): Twin satellites launched in March 2002, designed to make detailed measurements of Earth's gravity field. These measurements support discoveries and gravity and Earth's natural systems.

Great Observatories: A NASA program to launch four major observatories to cover the optical (Hubble Space Telescope), gamma-ray (Compton Gamma Ray Observatory), x-ray (Chandra), and infrared (Space Infrared Telescope Facility) portions of the electromagnetic spectrum.

half power diameter: The diameter of a circle containing 1/2 of the flux or counts from a point source.

hard x-rays: The highest-energy x-rays. Lower-energy x-rays are referred to as soft x-rays. The distinction between the two is not well defined, though hard x-rays are typically those with energies greater than around 10 keV.

Herschel Space Observatory: A 3.5-meter space telescope covering a spectral range from the far infrared to the submillimeter.

High Energy Focusing Telescope (HEFT): A balloonborne experiment that images astrophysical sources in the hard x-ray (20-100 keV) band.

Hubble parameter: A time-dependent parameter that, when multiplied with the distance to a given galaxy, yields the speed at which that galaxy is receding from Earth.

Hubble Space Telescope (HST): A 2.4-m-diameter space telescope designed to study visible, ultraviolet, and infrared radiation; the first of NASA's Great Observatories.

inflation period: An early era when the universe expanded by some 30 orders of magnitude in linear scale, creating nearly all particles and radiation. According to theory, inflation produced gravitational radiation.

inflationary universe, inflationary paradigm: An extension of the big bang model characterized by a tremendous burst of expansions. The underlying cause of inflation is not known, although there are many models for it based on particle physics.

INTEGRAL mission: A space observatory that simultaneously observes objects in gamma rays, x-rays, and visible light. The mission is sponsored by the European Space Agency and was launched in 2002.

interferometer, interferometry: A technique used to combine multiple beams of light that extracts information from differences in characteristics as the light beams arrive at the detectors. A spatial interferometer combines beams of light from different telescopes to synthesize the aperture of a single large telescope; see *array*. Spatial interferometry is the main technique used by astronomers to map sources at high resolution and to measure their positions with high precision. A different form of a single telescope can be used to separate light into its constituent colors; see *spectroscopy*.

intergalactic medium: Diffuse gas in the regions between galaxies, made up primarily of hydrogen and helium atoms. It is believed to contain most of the atoms of the universe.

International Traffic in Arms Regulations (ITAR): A rule administered by the U.S. Department of State that regulates the export and import of defense-related articles. These articles include launch vehicles, spacecraft, and associated equipment.

Keck Telescopes: A pair of 10-m-aperture optical and infrared telescopes located on the summit of Mauna Kea, Hawaii.

Kepler Telescope: A NASA Discovery mission specifically designed to survey our region of the Milky Way Galaxy to detect and characterize hundreds of Earth-size and smaller planets in or near the habitable zone. The orbiting telescope will have a 0.95-m diameter. It is scheduled to launch in November 2008.

Lagrange point: A point where a third mass can orbit in a fixed position, relative to two larger masses (such as Earth and the Sun); that is, the gravitational forces are balanced.

Large Synoptic Survey Telescope (LSST): A proposed ground-based telescope that will provide digital imaging of faint astronomical objects. It will track objects that change or move on rapid time scales, and it will also investigate dark matter and dark energy.

Laser Interferometer Gravitational-Wave Observatory (LIGO): Interferometric gravitational wave detector built at sites in the states of Washington and Louisiana; initial operation of the detectors began in 2001.

LISA Pathfinder (LP): A European Space Agency mission scheduled for launch at the end of 2009. The Laser Interferometer Space Antenna (LISA) Pathfinder will work on developing gravitational-wave measuring technologies that will later be used in the LISA mission.

lookback time: The apparent time being observed when light is received from distant objects. Due to the time that it takes an object's light to travel to Earth, the more distant an object being observed, the older the information received from it. Therefore, an object *X* light-years away is seen as it was *X* years ago.

low Earth orbit (LEO): Altitudes between 250-300 km and 1,000 km above sea level.

luminosity distance: The distance to a celestial object calculated using the object's luminosity (usually determined by using a standard candle).

Lunar Reconnaissance Orbiter (LRO): Planned for launch in 2008, this is the first NASA mission in the series of planned missions to the Moon. It would spend at least 1 year in low polar orbit around the Moon as it collected detailed information on the lunar environment.

Lyman-alpha forest: The dense abundance of hydrogen absorption lines apparent in the spectra of galaxies and quasars. Lyman-alpha lines are caused by the absorption of light at a particular wavelength by hydrogen ions containing a single electron. The Lyman-alpha forest occurs when a galaxy emits light that must travel through intergalactic gas (commonly occurring in the vast amounts of space between the Milky Way and other galaxies) before reaching telescopes at Earth. Because the universe is expanding, the absorption lines observed on Earth are slightly redshifted (see *redshift*) from the wavelength that would be observed if the universe were not expanding (1,216 angstrom). By calculating both the redshifted difference and how the universe is expanding, scientists can determine where the intervening hydrogen gas region is located.

magnetars: Neutron stars with magnetic-field strengths roughly a thousand trillion times stronger than those of Earth.

magnetosphere: The extent of a planet's magnetic field.

Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission: The first spacecraft to travel to Mercury, where it will study the geology and environment of Mercury. Launched in 2004, it will complete its first Mercury flyby in January 2008 and complete Mercury orbit insertion in 2011.

metallicity: A star's abundance of metals.

Near Field Infrared Experiment (NFIRE): Sponsored by the Missile Defense Agency and launched in 2007, it will gather high-resolution data that will assist in the development of missile defense applications.

neutron star: A star at such high density and pressure that its atoms have been completely crushed, until the nuclei merge and most of the electrons have been squeezed onto the protons, forming neutron-rich material.

New X-ray Telescope (NeXT): A Japanese mission that would provide the first imaging spectroscopy in the hard x-ray band above 10 keV and also achieve unprecedented observing capability in the soft x-ray band below 10 keV. It would cover the same x-ray energies as the Constellation-X Hard X-ray Telescope but with an effective area at least an order of magnitude smaller, poorer angular resolution, and a smaller field of view, limiting it to studying only the brightest sources. Its proposed launch date is in 2011.

Phase A: NASA terminology for the conceptual design phase.

Phase B: NASA terminology for the preliminary design phase.

Phase C/D: NASA terminology for the full-scale development and production phase.

Phase E: NASA terminology for the mission operations and data-analysis phase.

Planck: A mission implemented by the European Space Agency and designed to measure the cosmic background radiation. With higher resolution and greater sensitivity than the Cosmic Background Explorer, it will test theories of the early universe and the origin of cosmic structure. It is scheduled to launch in July 2008.

polarization: A measure of direction of the transverse electric field of light. The electric field associated with polarized light is strong along one of two directions perpendicular to the direction that the light is traveling. Scattered light is always polarized to some degree, and hence the polarization of light can give some information about the path that the light has traveled to reach Earth. The cosmic microwave background is also slightly polarized.

probes: Envisioned as medium-scale missions that could be executed much faster, and for considerably less money, than the flagship Laser Interferometer Space Antenna and Constellation-X missions.

pulsar: A spinning neutron star that emits radiation in a beam. The sweeping action of the beam causes the object to pulse regularly, like a lighthouse beam, when viewed by an observer.

quark: Point-like, elementary constituents of mesons and baryons (e.g., neutrons and protons).

quasar: A very compact and extraordinarily luminous source of radiation in the nucleus of a distant galaxy. Quasars are believed to be powered by the *accretion* of gas onto massive black holes.

redshift: Radiation from an approaching object is shifted to higher frequencies (to the blue), while radiation from a receding object is shifted to lower frequencies (to the red). A similar effect raises the pitch of an ambulance siren as it approaches. The expansion of the universe makes objects recede so that the light from distant galaxies is redshifted. The redshift is parameterized by z, where the wavelength shift is given by the factor $(1 + z)$ times the wavelength.

reionization: A process by which the predominantly neutral intergalactic medium was ionized by the emergence of the first luminous sources.

ringdown waves: Waves emitted by a distorted final black hole as it settles down to a stationary state.

Röntgen satellite (ROSAT): Low Earth-orbiting x-ray telescope functioning in the 0.1- to 2.0-keV range. An international mission involving Germany, the United States (NASA), and the United Kingdom, it was launched in 1990.

SIGMA telescope: A high-energy observing telescope created by French astronomers.

Sloan Digital Sky Survey (SDSS): A full-sky survey being completed by a 2.5-m telescope. When completed, the survey will provide detailed optical images covering more than a quarter of the sky, and a three-dimensional map of about a million galaxies and quasars. As the survey progresses, the data are released to the scientific community and the general public in annual increments.

Solar Dynamics Observatory: A NASA spacecraft carrying a suite of instruments designed to investigate the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. It is scheduled for launch in August 2008.

solar flare: Short, intense brightening of the solar photosphere near a sunspot, caused by the release of large amounts of energy from a small area of the Sun's surface.

spacetime: The four-dimensional continuum in which we live, consisting of the three dimensions of space and one dimension of time.

special relativity: Einstein's theory of spacetime structure, in which Newton's notion of absolute time is abandoned to account for the experimental fact that the speed of light is a universal constant and does not depend on the relative motion between the observation and the light source.

spectroscopy: A technique whereby the light from astronomical objects is separated by wavelength into its constituent colors. Radiation from the different chemical elements that make up an object can be distinguished, giving information about the abundance of these elements and their physical state.

Spitzer Space Telescope: A 0.85-m infrared telescope launched by NASA in August 2003.

Square Kilometer Array: A proposed ground-based radio telescope that will be composed of an interferometric array of individual antenna stations with a combined square kilometer of collecting area, synthesizing an aperture with diameter of up to several thousand kilometers. Early science is expected to begin in 2014, and it is scheduled to be fully operational in 2020.

standard candle: A celestial object whose intrinsic brightness is known or can be estimated by some physical principle and whose observed brightness is therefore useful as a tool to measure distance.

Standard Model of Physics: The theory that summarized the current picture of the field of elementary-particle physics. It includes three generations of quarks and leptons, the electroweak theory of weak and electromagnetic forces, and the quantum chromodynamic theory of the strong force. It does not include answers to some basic questions such as how to unify electroweak forces with the strong or gravitational forces.

sterile neutrinos: A hypothetical neutrino that does not interact with other particles. It is also a candidate dark matter particle.

supermassive black hole: A black hole that is much more massive than the Sun. Supermassive black holes with masses exceeding a million solar masses are found in the nuclei of most galaxies.

supernova remnant (SNR): The remains of supernova explosions, SNRs are extremely important for understanding our Galaxy. They heat up the interstellar medium, distribute heavy elements throughout the Galaxy, and accelerate cosmic rays.

Suzaku: A Japanese x-ray satellite, launched in 2005, developed through Japan-U.S. international collaboration. The satellite's goals are to study hot plasma in the x-ray and gamma-ray wavelengths, study the structure and evolution of the universe, and study black hole candidates and active galactic nuclei. Also called Astro-E2.

Swift mission: Launched by NASA in 2004; the goal of the Swift mission is to detect and analyze gamma-ray bursts.

Type Ia supernova: The thermonuclear explosion of a white dwarf star caused by the accretion of material from a binary companion. Type Ia supernovas (Snela) can be used as standard candles to chart the universe.

Type II supernova: A gigantic explosion that signals the death of a massive star. Often, the explosion leaves behind a neutron star; in other cases it may produce a black hole.

Very Large Telescope (VLT): Organized by the European Southern Observatory, all four telescopes in this array were operational beginning in 2006. The VLT consists of four 8 meter telescopes that can either work independently or in combined mode. Combined, the telescopes provide the light collecting power of a 16 meter telescope.

Virgo cluster: An irregular cluster of about 2,500 galaxies.

***w*:** Dark energy equation-of-state parameter that indicates how dark energy reacts to varying temperatures and densities.

warm dark matter: A theoretical type of dark matter particle with higher temperature and velocity than those of cold dark matter.

weak lensing: Gravitational lensing in which the lens is not strong enough to produce multiple images, but merely stretches the image of the background object.

Wide-field Infrared Survey Explorer (WISE): An infrared space observatory designed to be an all-sky survey in wavelengths from 3.5 to 23 microns that will be up to 1,000 times more sensitive than the Infrared Astronomical Satellite. Launch is scheduled for November 2009.

Wilkinson Microwave Anisotropy Probe (WMAP): Launched by NASA in 2001, the WMAP maps temperature fluctuations in the cosmic microwave background with very high precision; see *cosmic microwave background (CMB) radiation*.

X-ray Evolving Universe Spectroscopy (XEUS): A follow-up to the European Space Agency's Cornerstone X-Ray Spectroscopy Mission. It is a permanent spaceborne x-ray observatory whose goals are to probe dark matter and dark energy, to study massive blackholes at $z \sim 10$, to observe the structure of the galaxies near black holes, and to study matter under extreme conditions and the structure of highly collapsed stars.

X-ray Multi-Mirror Mission-Newton (XMM-Newton): Launched by the European Space Agency in 1999, the XMM-Newton carries three advanced x-ray telescopes. XMM-Newton has studied x-rays from accretion onto black holes, properties of exploding stars, the nature of exotic matter, and has observed gamma-ray bursts.

***z*:** See *redshift*.

zenith: The point on the celestial sphere directly above the observer, that is, opposite to the direction of gravity.

zodiacal light: Sunlight scattered by interplanetary dust in our solar system.

I

Biographies of Committee Members and Staff

CHARLES F. KENNEL (*Co-Chair*) is Distinguished Professor and former director at the Scripps Institution of Oceanography and the director of the Environment and Sustainability Initiative at the University of California, San Diego. He has an extensive background in environmental science, particularly in observational programs for global change research, and was associate administrator for NASA's Mission to Planet Earth enterprise in 1993-1996. Dr. Kennel was awarded the Aurelio Peccei Prize from the Accademia Lincei for this work. His earlier research on fundamental plasma physics combined with space and astrophysics was recognized by the James Clerk Maxwell Prize from the American Physical Society and the Hannes Alfven Prize from the European Geophysical Society. He has served on numerous boards and committees of the National Research Council (NRC), most recently as chair of the Committees on Global Change Research and on Fusion Science. He is a former chair of the NASA Advisory Council and, most recently, of its Science Committee.

JOSEPH H. ROTHENBERG (*Co-Chair*) is currently the president and a member of the board of directors of Universal Space Network. He spent 17 years with Grumman Aerospace and held a number of spacecraft development, testing, operations, and management positions that included both the Solar Max Mission and Orbiting Astronomical Observatory projects. In 1983, he joined the NASA Goddard Space Flight Center (GSFC) as the operations development manager for the Hubble Space Telescope (HST). In 1990 Mr. Rothenberg was selected as project manager for the first HST servicing mission. In 1995 he was named the director of GSFC and was responsible for space systems development and execution of the scientific research program for the NASA Earth-orbiting science missions. In January 1998, he moved to NASA Headquarters, where he was named associate administrator for space flight and was in charge of NASA's human exploration and development of space. As associate administrator, Mr. Rothenberg was responsible for establishing policies and direction for the Space Shuttle and International Space Station Programs, as well as for space communications and expendable launch services. Mr. Rothenberg served on the NRC Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope, and he is currently a member of the Committee on Meeting the Workforce Needs for the National Vision for Space Exploration.

ERIC G. ADELBERGER is an experimental physicist at the University of Washington. His research interests cover gravitational physics, the study of fundamental symmetries in nuclei, and nuclear astrophysics. Dr. Adelberger is known for his use of atomic nuclei as laboratories for studying fundamental symmetries and interactions and for his tests of high-precision gravitational forces. His current research involves experimental work in gravitational physics, nuclear astrophysics, low-energy tests of fundamental symmetrics, and nuclear structure. Dr. Adelberger was awarded the Tom W. Bonner Prize in nuclear physics and the von Humboldt Senior Scientist Award. He served on the NRC Task Group on Gravity Probe B and on the Committee on Gravitational Physics. Dr. Adelberger was a member of the Nuclear Science Advisory Committee to the Department of Energy (DOE) and the National Science Foundation (NSF) and a member of the NSF Special Emphasis Panel on Nuclear Physics.

WILLIAM B. ADKINS is president of Adkins Strategies, LLC, a space and defense consulting firm in Washington, D.C. Prior to forming Adkins Strategies, Mr. Adkins spent 20 years in government service in various capacities within the national security and civil space arenas. Mr. Adkins was a staff director for the Subcommittee on Space and Aeronautics on the House Science Committee, where he led the subcommittee's legislative and oversight activities of NASA and related space and aeronautics activities. Before joining the subcommittee, Mr. Adkins was a legislative assistant for Senator Spencer Abraham (R-Mich.). Before working on Capitol Hill, he worked at the National Reconnaissance Office and the Naval Research Laboratory, where he was involved in the development of space systems and advanced technology.

THOMAS APPELQUIST is a professor of physics at Yale University. His research has focused on the theory of elementary particles, including the strong interactions and electroweak unification. His most recent interests have dealt with universal extra dimensions and the origin of the quark and lepton masses. He chaired the NRC Board on Physics and Astronomy's Physics Survey Overview Committee.

JAMES S. BARROWMAN is currently an independent consultant. He worked at NASA Goddard Space Flight Center for 22 years in program and project management. At GSFC, he was involved in managing the Attached Shuttle Payloads Project, the Attached Payloads and Explorers Mission project, the Explorers Program, the Extreme Ultraviolet Explorer Satellite, and the Hubble Space Telescope missions. During his tenure at GSFC, he served as deputy director of the Space Science Directorate. He is the recipient of the NASA Outstanding Leadership Medal and two NASA Exceptional Service Medals. Mr. Barrowman is a member of the American Institute of Aeronautics and Astronautics and past president of the National Association of Rocketry. He served on the NRC Committee on Principal-Investigator-Led Missions in the Space Sciences: Lessons Learned.

DAVID A. BEARDEN is the principal director for NASA programs at the Aerospace Corporation, where he provides technical direction for the staff supporting NASA and Jet Propulsion Laboratory on interplanetary and Earth science programs. These programs include the Mars Program, Space Interferometry Mission, Outer Planets/Solar Probe Mission, New Millennium Program, Discovery programs, and other space physics and science missions. Dr. Bearden's expertise lies in the areas of project management, space systems architectural assessment, conceptual design and cost, and simulation and analysis of complex space systems. He joined the Aerospace Corporation in 1991 in the area of space concept analysis and design and later became a section manager in the Space Architecture Department.

MARK DEVLIN is a professor in the Department of Physics and Astronomy at the University of Pennsylvania. His research focuses on experimental cosmology at millimeter and submillimeter wavelengths. He designs and builds instrumentation and telescopes that are used in high-altitude balloons. He is currently involved in several projects for which he serves as principal investigator, including BLAST (Balloon-borne Large Aperture Submillimeter Telescope), ACT (Atacama Cosmology Telescope), Penn Array (a project to build a 90 GHz receiver for the National Radio Astronomy Observatory's 100 meter Green Bank Telescope), and PAPPA (Primordial Anisotropy Polarization Pathfinder Array).

JOSEPH FULLER, JR., is the founder and president of Futron Corporation, a decision-support consulting firm. The company designs innovative business and technical decision-support solutions to address some of the most challenging technology problems in the aerospace, defense, and transportation industries. Mr. Fuller began his career at NASA, where he spent 20 years as an aerospace systems engineer, project manager, and senior executive. He is experienced in the design, development, and operations of human- and robotic-piloted spacecraft. Space programs to which he has been a contributor include Gemini, Apollo, Skylab, the space shuttle, Television and Infrared Observation Satellite/National Oceanic and Atmospheric Administration, and the International Space Station. He is a recipient of the NASA Exceptional Service Medal. Mr. Fuller is a member of the Industrial Advisory Board of the University of Maryland Baltimore County, and a past member of the NRC Aeronautics and Space Engineering Board.

KARL GEBHARDT is a professor of astronomy at the University of Texas. His research covers the study of the central regions of galaxies and the search for dark energy using baryonic acoustic oscillations. He is the leader of the Hobby Eberly Telescope Dark Energy Experiment (HETDEX) that was designed to help researchers understand the evolutionary history of dark energy. HETDEX uses the Hobby Eberly Telescope to conduct a large redshift survey that can detect nearly 1 million galaxies over a huge volume. The goal of this research is to determine the expansion history of the universe using baryonic oscillations, thereby determining the evolution of dark energy. Dr. Gebhardt won a 2004 NSF Career Award and participated in the recent NSF Senior Review.

WILLIAM C. GIBSON is the vice president of the Space Science and Engineering Division at Southwest Research Institute. He has managed such projects as the High Altitude Plasma Instrument for the Dynamics Explorer Satellite, the Fast Ion Mass Spectrometer for the Centaur Rocket Project, and the Balloon-Borne Ultraviolet Stellar Spectrometer. In addition to these projects, he served as the project manager for the Imager for Magnetopause-to-Aurora Global Exploration. His areas of technical specialization include the design of spacecraft data systems, spacecraft telemetry and control systems, and spacecraft heat-transfer systems. Mr. Gibson was the architect of the multiprocessor SEPAC On-Line Data Analysis real-time telemetry ground station used during Shuttle Transportation System-9 and the lead design engineer on the Johnson Space Center Stratospheric Ozone Experiment. Mr. Gibson served as chair of the NASA Confirmation Review Board for the Galaxy Evolution Explorer Small Explorer mission and as a member of the standing review board for the NASA Advanced Composition Explorer mission. He was a member of the NRC Task Group on Principal Investigator-Led Earth Science Mission and the Committee on Earth Studies.

FIONA A. HARRISON is a professor of physics and astronomy in the Space Radiation Laboratory at the California Institute of Technology. Dr. Harrison's primary research interests are in experimental and observational high-energy astrophysics. She is developing optics and detectors for future balloon- and satellite-borne x-ray and gamma-ray missions. In addition, she has an active observational program in gamma-ray, x-ray, and optical observations of gamma-ray bursts, active galaxies, and neutron stars. She was a member of the NRC Committee on the Physics of the Universe.

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DENNIS McCARTHY is an aerospace consultant. He recently retired as vice president and director of engineering services for Swales Aerospace, where he was responsible for all engineering discipline support to NASA, universities, and industry. Mr. McCarthy worked at NASA GSFC in 1978-1990, in positions that included deputy project manager for the Cosmic Background Explorer and associate director for NASA's Space Sciences Directorate. In 1991 he became the program manager for the Hubble Space Telescope (HST) at NASA Headquarters. He returned to GSFC in 1992 and became deputy project manager for the HST Servicing Mission, and later deputy associate director of Flight Projects. In 1995-1998, he served as program director for Johns Hopkins University's first principal-investigator program, Far Ultraviolet Spectroscopic Explorer.

STEPHAN S. MEYER holds joint professorship in the Department of Astronomy and Astrophysics, the Department of Physics, and the Enrico Fermi Institute at the University of Chicago. Dr. Meyer's research is focused on the cosmic microwave background (CMB), and he is a member of the Wilkinson Microwave Anisotropy Probe science team. He is also involved in the Extragalactic Diffuse Emission Experiment that is designed to measure the large-scale structure of the cosmic infrared background radiation, which will provide a new probe of structure growth, galaxy and star formation, and dust emission at redshifts. Dr. Meyer is involved in the South Pole Telescope project to map clusters of galaxies using the Sunyaev-Zeldovich effect and measure CMB polarization. He is currently a member of the NRC Committee on Astronomy and Astrophysics.

JOEL R. PRIMACK is a professor of physics at the University of California, Santa Cruz. His research covers relativistic quantum field theory, cosmology, and particle astrophysics. In collaboration with colleagues from astronomy, he developed the "cold dark matter" theory. Currently he has been investigating the implications of various hypotheses regarding the identity of dark matter for the formation and distribution of galaxies, and he is a member of a team that is exploring the cultural implications of the ongoing revolution in cosmology. Dr. Primack is the co-editor of *Dark Matter in the Universe* (1995) and co-author of *Advice and Dissent: Scientists in the Political Arena* (1972), and of *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos* (2006).

LISA J. RANDALL is a professor of theoretical physics at Harvard University. Her research covers elementary particles and fundamental forces, with the most recent involving extra dimensions of space. She has also worked on supersymmetry, Standard Model observables, cosmological inflation, baryogenesis, grand unified theories, general relativity, and string theory. Dr. Randall recently completed a book entitled *Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions* (2005).

CRAIG L. SARAZIN is the W.H. Vanderbilt Professor of Astronomy at the University of Virginia. He is a theoretical and observational astrophysicist whose areas of research include interstellar medium, clusters of galaxies, x-ray emission, and extragalactic astronomy. Dr. Sarazin served as chair or as a member of numerous scientific committees, including the Universities Space Research Association's Astronomy and Space Physics Science Council, the Chandra X-Ray Observatory Users' Committee, and the Extragalactic Proposal Review Panel for Hubble Space. He was a member of the NRC Committee on Space Astronomy and Astrophysics and the Panel on High-Energy Astrophysics from Space of the Astronomy and Astrophysics Survey Committee.

JAMES S. ULVESTAD is the assistant director of the National Radio Astronomy Observatory (NRAO) and the director of Very Large Array (VLA) and Very Long Baseline Array (VLBA) operations. As the director of VLA/VLBA operations, he has responsibility for all aspects of the VLA and VLBA, including the Expanded Very Large Array project. Before undertaking his position at NRAO, Dr. Ulvestad spent 12 years at the Jet Propulsion Laboratory working on topics such as very long baseline interferometry (VLBI), VLA arraying for the Voyager-Neptune encounter, VLBI astrometry, and optical interferometry. His primary research interests include Seyfert and starburst galaxies and compact radio emission from extragalactic gamma-ray sources.

CLIFFORD M. WILL is the James S. McDonnell Professor of Physics and a member of the McDonnell Center for the Space Sciences at Washington University in St. Louis. His research is on general relativity and its applications to astrophysics, gravitational radiation, black holes, cosmology, and experimental tests of general relativity. Dr. Will served on the NRC Committee on Gravitational Physics, the Committee on Physics of the Universe, and the Fundamental Physics Panel of the Task Group on Space Astronomy and Astrophysics; he currently serves as chair of the NASA Science Advisory Committee for Gravity Probe B. He served as chair of the American Physical Society Topical Group on Gravitation and is currently the president of the International Society on General Relativity and Gravitation. Dr. Will is a fellow of the American Physical Society and of the American Academy of Arts and Science.

MICHAEL S. WITHERELL is vice chancellor for research and a professor of physics at the University of California, Santa Barbara. He is an experimental particle physicist and a former director of Fermilab. He pioneered the development of silicon-strip detector technology, using it to perform precise studies of the production and decay of particles that carry the charm quark. Dr. Witherell served on the NRC Committee on Elementary Particle Physics.

EDWARD L. WRIGHT is a professor of astronomy at the University of California, Los Angeles. Dr. Wright's research interests are in theoretical and experimental infrared astronomy and cosmology, especially cosmic microwave background radiation studies. He played a major role on the NASA Cosmic Background Explorer (COBE) mission, and in 1992 he received the NASA Exceptional Scientific Achievement Medal for this work. He is a co-investigator on NASA's Wilkinson Microwave Anisotropy Probe, a mission that is a follow-up to the COBE discovery of fluctuations in the early universe. Dr. Wright participated in the Joint Efficient Dark-energy Investigation, and he is an interdisciplinary scientist on the NASA Space Infrared Telescope Facility (now the Spitzer Space Telescope) Science Working Group. His NRC experience includes membership on the Panel on Ultraviolet, Optical, and Infrared Astronomy from Space; the Committee on Physics of the Universe; and the Panel on Astronomy and Astrophysics of the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion. Dr. Wright is the principal investigator for the Wide-field Infrared Survey Explorer MidEx mission to be launched in 2009.

Staff

MARCIA S. SMITH is the director of the Space Studies Board and the Aeronautics and Space Engineering Board. Prior to joining the NRC in March 2006, Ms. Smith was a senior level specialist in aerospace and telecommunications policy for the Resources, Science, and Industry Division of the Congressional Research Service (CRS) at the Library of Congress, Washington, D.C. She had been with CRS since 1975, serving as a policy analyst for the members and committees of the U.S. Congress on matters concerning U.S. and foreign military and civilian space activities, and on telecommunications issues including the Internet (and formerly on nuclear energy). From 1985-1986, Ms. Smith took a leave of absence to serve as executive director of the U.S. National Commission on Space. Ms. Smith is the North American editor for the quarterly journal Space Policy. She is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), the American Astronautical Society (president, 1985-1986), and the British Interplanetary Society. She was awarded the AAS John F. Kennedy Astronautics Award in 2006. She was a founder of Women in Aerospace (WIA), its president (1987), a member of its board of directors (1984-1990), and was awarded its Lifetime Achievement Award in 2003. She is also a member of the International Institute of Space Law and the International Academy of Astronautics, and she is a life member of the New York Academy of Sciences and of the Washington Academy of Sciences. She is a member of Sigma Xi. She was a member of the NRC Committee on Human Exploration (1992-1993 and 1996-1997). A graduate of Syracuse University, Ms. Smith is the author or co-author of more than 220 reports and articles on space, nuclear energy, and telecommunications and Internet issues.

DONALD C. SHAPERO is director of the Board on Physics and Astronomy. He received a B.S. degree from the Massachusetts Institute of Technology (MIT) in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., he became a Thomas J. Watson Postdoctoral Fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University, and then joining the staff of the NRC in 1975. Dr. Shapero took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Physical Society (APS), the American Astronomical Society, the American Association for the Advancement of Science (AAAS), and the International Astronomical Union and is a fellow of the AAAS and the APS. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

BRIAN D. DEWHURST joined the National Research Council in 2001 and is a senior program associate with the Board on Physics and Astronomy. He is the staff officer and study director for a variety of NRC activities, including the Committee on Astronomy and Astrophysics, the Committee on Radio Frequencies, and other astronomy-oriented tasks. He received a B.A. in astronomy and history from the University of Virginia in 2000 and an M.A. in science, technology, and public policy from George Washington University in 2002. He joined the staff of the Space Studies Board as a research assistant in 2001 and transferred to his current position with the Board on Physics and Astronomy in 2002.

SANDRA J. GRAHAM has been a senior program officer at the Space Studies Board since 1994. During that time Dr. Graham has directed a large number of major studies, many of them focused on space research in biological and physical sciences and technology. More recent studies include an assessment of servicing options for the Hubble Space Telescope, reviews of the NASA roadmaps for space sciences and the International Space Station, and a review of NASA's Space Communications Program while on loan to the Aeronautics and Space Engineering Board. Before receiving her Ph.D. in inorganic chemistry from Duke University in 1990, she carried out research focused primarily on topics in bioinorganic chemistry, such as the exchange mechanisms and reaction chemistry of biological metal complexes and their analogs. From 1990 to 1994, she held the position of senior scientist at the Bionetics Corporation, where she worked in the science branch of the Microgravity Science and Applications Division at NASA Headquarters.

PAMELA L. WHITNEY, study director (through January 2007), was a senior program officer at the Space Studies Board, where she directed studies and workshops on international cooperation in space, Earth remote sensing, Mars planetary protection, and space policy, among other space technology and research topics. Ms. Whitney also served as the executive secretary of the U.S. National Committee to the Committee on Space Research (COSPAR) of the International Council for Science (ICSU). Previously, she held positions as an analyst at the aerospace consulting firm CSP Associates, Inc., and as a researcher and writer for Time-Life Books, Inc. Ms. Whitney was president of Freelance Unlimited and conducted work with the National Geographic Society, the World Bank, and the U.S. Congress's Office of Technology Assessment. She holds an A.B. in economics from Smith College and an M.A. in international communication from American University. She is a member of Women in Aerospace and a corresponding member of the International Academy of Astronautics.

VICTORIA SWISHER is a research associate. She has supported Space Studies Board studies and workshops on the NASA workforce, Mars research, research enabled by the lunar environment, and other topics. Before joining the Space Studies Board, she did research in x-ray astronomy and laboratory astrophysics, which included studying the x-rays of plasma and culminated in her senior thesis, "Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment." A graduate of Swarthmore College, she majored in astronomy and minored in English literature.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

CARMELA J. CHAMBERLAIN has worked for the National Academies since 1974. She started as a senior project assistant in the Institute for Laboratory Animals for Research, which is now a board in the Division on Earth and Life Sciences. After working there for 2 years, she transferred to the Space Science Board, now the Space Studies Board (SSB). She is now an program associate with the SSB.

CELESTE A. NAYLOR joined the NRC and the Space Studies Board in June 2002 as a senior project assistant. She has worked with the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope, the Committee on Astronomy and Astrophysics, the Committee on Microgravity Research, and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has more than 7 years of experience in event management.