# Assessment of a Plan for U.S. Participation in Euclid

NATIONAL RESEARCH COUNCIL
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Committee on the Assessment of a Plan for U.S. Participation in Euclid
Space Studies Board
Board on Physics and Astronomy
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

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# Preface

The formation of the National Research Council's (NRC's) Committee on the Assessment of a Plan for U.S. Participation in Euclid was requested by NASA at the November 9, 2011, meeting of the NRC's Space Studies Board and the Board on Physics and Astronomy. The committee was tasked to:

> Determine whether a proposed NASA plan for a U.S. hardware contribution to the European Space Agency (ESA) Euclid mission, in exchange for U.S. membership on the Euclid Science Team and science data access, is a viable part of an overall strategy to pursue the science goals (dark energy measurements, exoplanet detection, and infrared survey science) of the New Worlds, New Horizons report's top-ranked, large-scale, space-based priority: the Wide Field Infrared Survey Telescope (WFIRST).

Owing to the mid-February deadline for NASA's preliminary confirmation to the European Space Agency (ESA) of its interest in participating in the Euclid mission—with a view to a formal exchange of agreements in the Spring following interagency negotiations between NASA and ESA and the completion of the necessary U.S. interagency process to secure the U.S. government's approval of the resulting agreement—the committee was assembled on an expedited schedule. The committee held its first and only meeting in Washington, D.C., on January 18-20, 2012, with the intention of completing and releasing its report by the end of January. The assembled committee comprised former members of the Committee for the Decadal Survey of Astronomy and Astrophysics and other individuals with relevant scientific expertise, including some who served on the survey's relevant panels.

It was clear to the committee from the early stages of this study that it would be impossible to fulfill the task in determining whether a hardware contribution to Euclid is a viable part of an overall strategy to pursue the science goals of WFIRST without discussing both Euclid and WFIRST in detail. That realization was the core thrust behind how the agenda for its meeting was assembled. At that meeting the committee heard from experts and stakeholders from both Europe and the United States. On short notice, these individuals graciously agreed to attend (either in person or remotely) and (1) made presentations in response to questions prepared in advance by the committee, (2) answered additional questions from the committee members, and (3) provided their own candid observations on relevant matters. In its deliberations, the committee made use not only of the testimony of these experts (see Appendix C), but also of the decadal survey report, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH), itself. The committee was also keenly aware that it was not charged to consider any alterations to the NWNH science priorities. The committee understood that the survey committee was aware of Euclid's development and its science goals and that NWNH did not recommend Euclid as sufficient to satisfy the survey's science priorities. The committee also understood that it was not charged to make recommendations to the European Space Agency. Neither was it charged to make any recommendations on the current NASA planning for the WFIRST mission.

On a personal note I would like to thank my colleagues on the committee who agreed on short notice to participate in this expedited process. This commitment required in some cases considerable disruption not only to their schedules on the days of the meeting but also in the days that followed as we assembled this report. I would also like to thank the staff of the Space Studies Board and the Board on Physics and Astronomy, most notably David Lang, Caryn Knutsen, and Dionna Williams, whose out-of-hours attention to this report made meeting the deadline possible.

David N. Spergel, *Chair*
Committee on the Assessment of a Plan for U.S. Participation in Euclid

## 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 Report Review Committee of the National Research Council (NRC). 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 review of this report:

David Bennett, University of Notre Dame,
Roger Blandford, Stanford University,
Adam Burrows, Princeton University,
James Green, University of Colorado,
Charlie Kennel, Scripps Institution of Oceanography and University of California, San Diego,
Robert C. Kennicutt, Jr., University of Cambridge, U.K.,
Paddy Leahy, University of Manchester, U.K.,
Adam Riess, Space Telescope Science Institute, Johns Hopkins University,
Michael S. Turner, University of Chicago, and
C. Megan Urry, Yale University.

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. Appointed by the NRC, she was 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

NASA has proposed to make a hardware contribution to the European Space Agency's (ESA's) Euclid mission in exchange for U.S. membership on the Euclid Science Team and science data access.

The Euclid mission will employ a space telescope that will make potentially important contributions to probing dark energy and to the measurement of cosmological parameters. Euclid will image a large fraction of the extragalactic sky at unprecedented resolution and measure spectra for millions of galaxies.

This report responds to a request from NASA to evaluate whether a small investment in Euclid (around $20 million in hardware) is a viable part of an overall strategy to pursue the science goals of the New Worlds, New Horizons (NWNH) report's top-ranked large-scale, space-based priority: the Wide-Field Infrared Survey Telescope (WFIRST). WFIRST has a broad, wide-field, near-infrared capability that will serve a wide variety of science programs of U.S. astronomers, including exoplanet research, near-infrared sky surveys, a guest observer program, and dark energy research. In carrying out this study the committee's intent has been to be clear that this report does not alter NWNH's plans for the implementation of the survey's priorities.

The Committee on the Assessment of a Plan for U.S. Participation in Euclid concludes that the NASA proposal would represent a valuable first step toward meeting one of the science goals (furthering dark energy research) of WFIRST.

While WFIRST dark energy measurements are expected to be superior to Euclid's, U.S. participation in Euclid will have clear scientific, technical, and programmatic benefits to the U.S. community as WFIRST and Euclid go forward.

**NASA should make a hardware contribution of approximately $20 million[1] to the Euclid mission to enable U.S. participation. This investment should be made in the context of a strong U.S. commitment to move forward with the full implementation of WFIRST in order to fully realize the decadal science priorities of the NWNH report.**

**In exchange for this small, but crucial contribution, NASA should secure through negotiation with the European Space Agency both a U.S. position on the Euclid Science Team with full data access and the inclusion of a team of U.S. scientists in the Euclid Consortium that would be selected by a peer-reviewed process with full data access as well as authorship rights consistent with Euclid policies still to be formulated.**

**NASA should seek independent community review of any financial commitment for hardware expenditures beyond $30 million for Euclid.**

# 1
# Background

The 2010 Astronomy and Astrophysics Decadal Survey (Astro2010) report *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH) recommended the Wide-Field Infrared Survey Telescope (WFIRST) as the top-ranked, space-based, large-scale activity for the coming decade. The WFIRST mission is designed to significantly advance our understanding of the origin of cosmic acceleration, to illuminate the formation and evolution of planetary systems, and to carry out powerful near-infrared surveys and conduct a guest observer program, thereby enabling a wealth of astrophysical discoveries. Soon after the release of NWNH, cost overruns and schedule delays in the James Webb Space Telescope and changes in the NASA budgets substantially reduced the anticipated funding available to NASA for new initiatives for much of the rest of the decade. The resulting cost constraints have delayed the anticipated launch date of WFIRST to the first half of the 2020 decade.

During the process of the NWNH decadal survey, the European Space Agency (ESA) was considering Euclid for implementation as one of its next M(edium)-class missions. The decadal survey report mentions possible U.S. involvement with the Euclid mission in three sections:

> The European Space Agency (ESA) is considering an M-class proposal, called Euclid, with related goals. Collaboration on a combined mission with the United States playing a leading role should be considered so long as the committee's recommended science program is preserved and overall cost savings result.[2]

> Euclid is a European mission concept aimed at cosmology and dark energy, which is competing for one of two M(edium)-class launch slots, with a decision expected in late 2011 and launches scheduled for 2018 and 2019. The overlap in goals and scope between the proposed U.S. and European missions is significant, and there is potentially a grand partnering arrangement involving NASA, DOE, and ESA if the expanded scientific priorities set by Astro2010 for such a mission can be aligned among the partners, and assuming that the arrangement is consistent with the United States playing a clear leadership role.[3]

> There have been discussions between the U.S. agencies and ESA about mounting a joint mission, which could be a positive development if it leads to timely execution of a program that fully supports all of the key science goals of WFIRST (planet microlensing, dark energy science, general investigations) and leads to savings overall. It is expected that the United States will play a leading role in this top-priority mission.[4]

After the publication of the decadal survey report, NASA reported results of negotiations (carried on during the decadal deliberations) with ESA for a possible 20 percent NASA contribution to the Euclid mission. The Office of Science and Technology Policy requested that the National Research Council (NRC) convene a panel to evaluate whether NASA's Euclid proposal is consistent with achieving the priorities, goals, and recommendations, and with pursuing the science strategy, articulated in NWNH. The Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey (hereafter, the Implementation Panel) concluded in December 2010:

> A 20 percent investment in Euclid as currently envisioned and as presented by NASA is not consistent with the program, strategy, and intent of the decadal survey. NWNH stated the following if the survey's budget assumption cannot be realized: "In the event that insufficient funds are available to carry out the recommended program, the first priority is to develop, launch, and operate WFIRST, and to implement the Explorer program and core research program recommended augmentations." A 20 percent plan would deplete resources for the timely execution of the broader range of NWNH space-based recommendations and would significantly delay implementing the Explorer augmentation, as well as augmentations to the core activities that were elements in the survey's recommended first tier of activities in a less optimistic budget scenario. A 20 percent contribution would also be a non-negligible fraction of the resources needed for other NWNH priorities.[5]

The economic and scientific landscape has changed in the year since the Implementation Panel report was released at the end of 2010. NASA announced the JWST replan during 2011. The WFIRST Science Definition Team (SDT) has spent the past year developing in greater detail a WFIRST reference mission design and characterizing its scientific potential. The SDT has presented an interim report.[6] In addition the NASA proposed level of investment in Euclid, as defined by the hardware contributions under consideration, is substantially smaller than discussed in the Implementation Panel report.

In October 2011, the European Space Agency selected Euclid as one of its M-class missions. At the November 7, 2011, joint meeting of the Space Studies Board and the Board on Physics and Astronomy, NASA again approached the NRC for advice regarding a potential plan for participation in the Euclid mission, at a significantly smaller level than in 2010, and asked the NRC to convene a committee to rapidly assess this plan. The NRC convened the Committee on the Assessment of a Plan for U.S. Participation in Euclid with the following statement of task:

> The [committee will] determine whether a proposed NASA plan for a U.S. hardware contribution to the European Space Agency (ESA) Euclid mission, in exchange for U.S. membership on the Euclid Science Team and science data access, is a viable part of an overall strategy to pursue the science goals (dark energy measurements, exoplanet detection, and infrared survey science) of the New Worlds, New Horizons report's top-ranked, large-scale, space-based priority: the Wide Field Infrared Survey Telescope (WFIRST).

This report addresses this charge and highlights several areas of opportunity as well as some concerns for the future. The next chapter reports the committee's findings. The final chapter reports the committee's conclusions and recommendations. The appendixes include a summary of the presentations to the committee.

The committee endorses a small investment in Euclid as a first step in a strategic program that leads to implementation of the WFIRST mission. The committee finds that this contribution is consistent with the recommendations of NWNH and the conclusions of the Implementation Panel in maintaining a U.S. leadership role in dark energy studies only in combination with moving forward with the WFIRST mission's dark energy program and its broader goals, as described in detail in this report.

The current recommendation differs from the conclusion of the Implementation Panel report because the current NASA proposal, to invest modestly in Euclid, is consistent with an expeditious development of WFIRST and the achievement of the broader, and more ambitious, goals outlined in NWNH.

# 2
# Findings

## THE PROPOSED EUCLID MISSION

**Finding:** The Euclid mission promises to make important contributions to probing dark energy and to the measurement of cosmological parameters.

The Euclid payload includes a 1.2-m obscured-aperture telescope, an optical array of 36 4k x 4k charge-coupled devices (CCDs) with 0.1 arcsec pixels, and an infrared array with 16 2k x 2k HgCdTe sensors with 0.3 arcsec pixels. These arrays have fields of view of 0.56 square degrees and 0.55 square degrees. A filter wheel holds a grism for spectral resolution R ~ 250 spectroscopy in addition to the near-infrared Y-, J-, and H-band imaging filters.[7] The core science observations of the mission are planned to take 6.25 years. The European Space Agency (ESA) plans to launch Euclid in late 2019.[8]

Euclid will use both weak gravitational lensing and the large-scale distribution of galaxies (including baryon acoustic oscillations, BAO) to measure the geometry of the universe and a combination of weak gravitational lensing, redshift-space distortions, and galaxy cluster measurements to probe the growth rate of structure. Together, measurements of the growth of structure and the distance-redshift relation will constrain the nature of dark energy and the physical origin of cosmic acceleration. Euclid measurements should represent a very significant advance over current measurements of structure growth and the geometry of the universe. They have the potential to revolutionize our understanding of dark energy.

Euclid plans to carry out optical plus near-infrared (NIR) imaging observations over an area of 15,000 square degrees (NIR limiting magnitudes $YJH_{AB} = 24$) in order to obtain weak gravitational lensing shear measurements of ~1.5 billion galaxies. The statistical power of this technique to probe dark energy derives from the ability to measure cosmic shear in tomographic redshift slices. To maximize weak gravitational lensing signal-to-noise, Euclid visual imaging will be carried out in a single, broad optical band. Weak lensing measurements require both excellent image quality and very large uniform samples (ideally hundreds of millions) of galaxies. Euclid will be the first mission to attempt these challenging measurements in space for large numbers of galaxies and as such represents a significant advance in techniques for studying cosmic acceleration. Euclid's combined visible and near-infrared survey will have no precedent and will likely constitute the premier space-based dark energy survey until the Wide-Field Infrared Survey Telescope (WFIRST) is launched.

**Finding:** The Euclid mission will provide a valuable legacy of survey science data. These data can be expected to be a unique resource for the astronomical community.

Beyond its cosmological studies using BAO and weak-lensing measurements, Euclid will provide the astronomical community with extremely valuable survey data that can be exploited for a wide range of scientific investigations. Two surveys are planned for the Euclid mission:[9] a wide survey covering 15,000 square degrees of sky and a deep survey covering nominally 40 square degrees studying the

redshift 6-8 universe. Both surveys will be carried out in visible and near-infrared bands and also include spectroscopic measurements in the near-infrared. Figure 2.1 indicates the sensitivities for the Euclid wide survey; the deep survey will go approximately 6 times (2 magnitudes) fainter. The Euclid Wide Survey is expected to cover a larger area than will the WFIRST survey.

The Euclid surveys will be unprecedented, producing a massive data set of deep images and spectra covering a significant fraction of the sky. The Euclid Wide Survey will provide images of billions of galaxies at redshifts of $1 < z < 3$ and near-infrared spectroscopy of tens of millions of galaxies, thereby allowing determination of their redshifts. Its 0.13 arcsecond spatial resolution in the visible will be a significant improvement over ground-based surveys whose resolution is limited because of the atmosphere. The Euclid Deep Survey is designed primarily to detect and study a sample of high-redshift star-forming galaxies at $6 < z < 8$, thus providing new insights into galaxy formation and evolution at early epochs.[10] The Euclid surveys will be a unique resource for the astronomical community, not unlike the earlier Sloan Digital Sky Survey, and can be expected to impact all areas of astronomical research. In addition to the obvious impact on studies of galaxies at moderate and high redshifts, the Euclid surveys will also provide a vast catalogue of stars in our own Galaxy and in nearby galaxies, expected to make important contributions to studies of both galaxy structure and stellar populations.

U.S. participation in Euclid through the Euclid Science Team (EST) and Euclid Consortium (EC) could be very beneficial for the development of the tools and expertise within the U.S. astronomical community needed to effectively exploit the Euclid survey data when it becomes public, nominally 14 months after the start of the survey. Access to and widespread use of the Euclid survey data will help leverage the considerable investment made by the United States in both JWST and large ground-based projects such as Large Synoptic Survey Telescope (LSST) and the Atacama Large Millimeter Array.

## THE PROPOSED WFIRST MISSION

**Finding:** The Wide Field Infrared Survey Telescope (WFIRST) is a highly capable mission with an exciting and broad scientific program spanning exoplanets to cosmology to infrared surveys.

NWNH envisaged WFIRST to be a 1.5-meter obscured-aperture telescope; recent work by the Science Definition Team (SDT) has suggested an alternate 1.3-meter off-axis telescope design, with equivalent detecting area but a more compact point spread function.[11] In this new candidate design, the focal plane consists of 36 2k x 2k HgCdTe infrared detectors, of which 8 are dedicated to distinct spectroscopic channels with 0.45 arcseconds per pixel and spectral resolution $R \sim 200$.[12] The imaging scale is approximately 0.18 arcseconds per pixel with a 0.291 degree field of view. Spectroscopy is always enabled in parallel with the imaging arrays and covers 1.1 to 2.0 microns. A filter wheel for the imaging array also includes six filters and an additional $R \sim 75$ prism. WFIRST can take images and spectra over the 0.6 to 2.0 micron wavelength range.

WFIRST enables a broad spectrum of science and the large discovery potential of a guest observer program. The Euclid and WFIRST missions have different objectives, different hardware, and different survey designs. Euclid will make high-resolution optical images that are the key observation for its core program of using weak lensing to study dark energy. WFIRST use its near-infrared observations to address the broad research program outlined in NWNH.

## COMPARISON OF WFIRST AND EUCLID CAPABILITIES

**Finding:** Both Euclid and WFIRST should make important contributions to the understanding of cosmic acceleration. While Euclid should advance our understanding of

dark energy, WFIRST has the more robust and powerful approach. WFIRST should make significant advances in dark energy research beyond Euclid's own contributions.

In the report of the NWNH Science Frontiers Panel on Cosmology and Fundamental Physics, that panel noted that the key requirements for studying cosmic acceleration were measurements over a wide redshift range, rather than an emphasis on a redshift $z < 1$.[13] There have been no observational results since NWNH that argue for a major deviation from that panel's conclusions. There are three primary, complementary techniques for studying dark energy: weak gravitational lensing, three-dimensional clustering of galaxies, and supernova measurements. Only WFIRST will use all three, including the supernova technique used by U.S. astronomers and their colleagues in their Nobel Prize-winning discovery of cosmic acceleration. Supernova measurements complement the other two techniques and currently provide the strongest dark energy constraints; all three are needed for a robust dark energy program.

Both Euclid and WFIRST plan to use measurements of the three-dimensional distribution of galaxies to trace the geometry of the universe. During the first 400,000 years after the Big Bang, sound waves in the cosmic fluid imprint a structure known as baryon acoustic oscillations in the three-dimensional distribution of galaxies. Measurements of these BAO features provide a "standard ruler" for measuring the expansion rate of the universe as a function of time (or equivalently, redshift). According to the current plans of both missions, the Euclid mission would cover a wider area of the sky than the WFIRST mission.[14] Because the WFIRST mission delivers a higher number density of galaxies, the effective volume of its survey is larger; thus it will be better able to make the key measurement of the relationship between distance and redshift (z). The proposed WFIRST BAO survey will make significantly more accurate distance measurements than the Euclid BAO survey at redshifts $z > 1$, when the universe was approximately half its present age, and nearly an order of magnitude better at $z = 2$.[15] With its higher number density of galaxies, WFIRST will be better able to use redshift distortions to measure the growth rate of structure. The combination of growth rate measurements and geometry measurements tests whether cosmic acceleration is due to dark energy or the breakdown of general relativity.

Weak gravitational lensing, the distortion of the observed shapes of distant galaxies due to the bending of light rays by the clumpy distribution of matter, is a potentially powerful technique for tracing its large-scale distribution. The measurement of weak gravitational lensing is a primary objective of both the Euclid and the WFIRST missions. For Euclid this involves measuring the shapes of galaxies with optical CCDs. WFIRST measures the shapes of galaxies in the infrared, where galaxies are brighter and smoother. The WFIRST reference mission, as described in the interim report of the WFIRST SDT,[16] allocates 1 year of survey time for a wide-area weak gravitational lensing program in comparison to 6.25 years for Euclid. If limited by statistical errors, then the expected weak gravitational lensing dark energy science return will be somewhat greater from Euclid than WFIRST.[17] The weak gravitational lensing signal is very subtle, however, and its detection is vulnerable to systematic errors introduced by the instrument,[18] by the atmosphere (when observed from the ground), and by astrophysical effects such as intrinsic alignments.[19] The WFIRST multiband approach to weak gravitational lensing is more robust than Euclid's single very broad band, which is potentially vulnerable to galaxy color gradients.[20,21] Because WFIRST measures lensing in three passbands, its data can be internally cross-correlated to help mitigate systematic measurement error. Since the WFIRST approach to weak gravitational lensing measurement appears to be more robust, it may produce better constraints on dark energy properties.

Euclid's and WFIRST's measurements are not duplicative and the combinations will be more powerful than any single measurement. Combining WFIRST with Euclid and with ground-based data sets, such as that expected from LSST,[22] should further enable astronomers to address the systematic challenges that previous ground-based weak gravitational lensing measurements have experienced.[23] These combined data sets will likely overcome systematic limitations and realize the full potential of this powerful technique.

**Finding:** Euclid and WFIRST both will use a combination of ground-based optical measurements and space-based near-infrared measurements to determine the distances of galaxies observed in their weak gravitational lensing surveys.

An essential part of any weak gravitational lensing observation is an approximate determination of the distance (more precisely the redshift) to the lensed galaxy. Both Euclid and WFIRST must augment their space-based near-infrared galaxy observations with ground-based optical data in order to obtain approximate estimates of distance known as photometric redshifts (photo-z's).

The Euclid mission plans to obtain the needed multiband optical data over its survey area from a combination of ground-based observatories. A number of facilities are carrying out, planning, or considering wide-area, multiband, optical surveys to a depth useful for Euclid photo-z's, including Pan-STARRS,[24] Dark Energy Survey (DES),[25] LSST,[26] KIDS,[27] HyperSubprimeCam,[28] and the William Herschel Telescope.[29] The first three of these are U.S.-led projects, and each has had independent discussions with the Euclid mission about the possibility of collaboration. In the same timeframe as Euclid and WFIRST, LSST should also carry out its deeper optical survey. There are clear, but notably asymmetric, potential synergies between these projects and Euclid: multiband optical data from the ground are necessary for Euclid to meet its weak gravitational lensing science requirements; on the other hand, while Euclid data would enhance the science reach of the ground-based surveys, those data are not seen as necessary to achieving the primary science goals of those surveys. These same considerations apply to WFIRST and the ground-based surveys.

**Finding:** Critical elements of the WFIRST mission are outside the scope of Euclid's core science mission. WFIRST's guest observer program will enable a broad range of astronomical science; its gravitational microlensing survey for exoplanets will provide an essential complement to Kepler[30] in detecting Earth-mass planets at a wide range of separations, from the habitable zone to infinity; and its deep infrared surveys are well matched to the LSST optical survey. Among the other unique aspects of the WFIRST mission are its supernovae survey and its survey of the galactic plane.

Surveys of large areas of the sky enable a wide range of astronomical studies. During the past decade, the Sloan Digital Sky Survey (SDSS), a ground-based optical survey, was by some metrics the most productive astronomical instrument in the world.[31] U.S. astronomers are leading several deeper optical surveys (Pan-STARRS and DES) that will map the sky much more sensitively than SDSS. The NWNH's top priority for large ground-based astronomy projects is the LSST, which will undertake a very deep optical survey of the sky (as well as time domain studies).

While optical surveys are essential for many areas of science, much of today's forefront astronomical science requires NIR data to further understanding. Earth's atmosphere is quite bright in the NIR (in addition to blurring the images), which significantly hampers ground-based NIR observations. While Euclid's infrared imaging data will enable an important wide survey, its 0.3 arcsecond pixels do not fully sample its point spread function and effectively smear out galaxy images. WFIRST takes full advantage of the space environment by surveying the sky in three NIR filters at high resolution with a well-sampled point spread function. As shown in Figure 2.1, WFIRST's NIR surveys are substantially deeper than Euclid's (with higher spatial resolution) and, importantly, are well matched in depth to the optical surveys planned by the LSST, although they cover less area. WFIRST should, for instance, revolutionize studies of galaxy formation and evolution during the epoch when galaxies such as the Milky Way were most vigorously forming stars.[32] WFIRST will map the structure of the Galaxy using red giant clump stars as tracers and will probe the epoch of reionization by detecting bright quasars and the most massive galaxies shining less than half a billion years after the Big Bang. The versatility and sensitivity of WFIRST's wide-field NIR camera and spectrometers are crucial for enabling a robust Guest Observer program, with at least 10 percent of the mission lifetime available to the community through peer-reviewed, open competition.

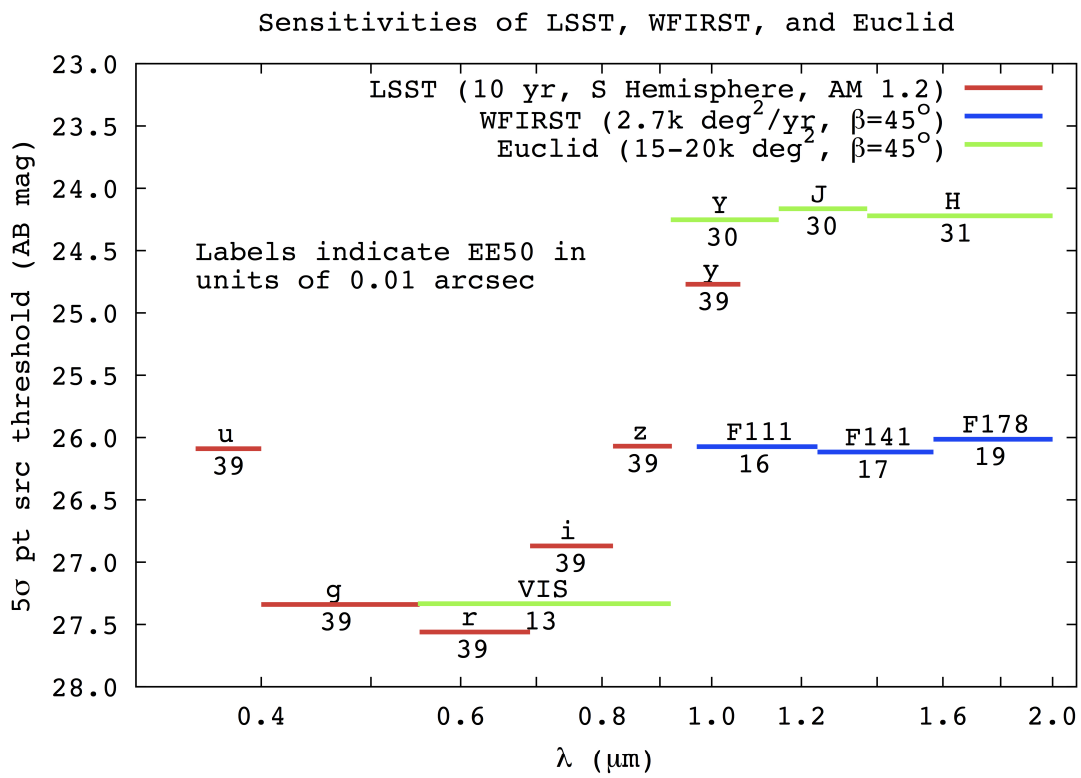


FIGURE 2.1 The point source sensitivity of various planned weak gravitational lensing surveys: LSST *(red)*, WFIRST deep *(blue)* and Euclid wide *(green)*. Magnitudes are defined so that fainter objects have larger magnitudes. LSST, Euclid's broad band optical images, and WFIRST deep survey will be able to see fainter galaxies than Euclid's wide survey. The WFIRST deep survey goes deeper, but the Euclid survey covers a much larger area. SOURCE: Courtesy of Chris Hirata, California Institute of Technology.

WFIRST with its three infrared colors and optimized survey capability will be an excellent tool for a variety of modest area (a few square degrees) Guest Observer projects such as mapping galaxy clusters, mapping nearby galaxies much more deeply and with much better spatial resolution than a variety of current Milky Way observational projects. As is usual for new capabilities such as WFIRST will offer, the Guest Observer program will undoubtedly lead to discoveries in unanticipated areas.

WFIRST should also significantly advance the census of exoplanets through gravitational microlensing searches. The field of exoplanets has enjoyed rapid and exciting progress during the past decade, with NASA's recently launched Kepler mission providing the observations that are currently driving the field. Kepler is sensitive to planets in orbits whose semi-major axis are comparable to or smaller than 1 AU, Earth's distance from the Sun. WFIRST's gravitational microlensing search will detect planets in orbits not accessible to Kepler. Specifically, the gravitational microlensing technique is sensitive to planets in orbits with semi-major axes larger than ~1 AU, where Kepler's transit technique is less effective.[33] The combination of Kepler and WFIRST survey data will allow a comprehensive census of the prevalence of planets in orbits ranging from very close to their parent stars out to and beyond the "snow line," where ice formed in the proto-planetary disk.[34] WFIRST will also determine the space density of free-floating planets (i.e., planets not bound to individual stars). Euclid does not currently have plans to conduct a search for exoplanets, and, in any case, the Euclid telescope's small field of regard (i.e., viewable sky angle) would make gravitational microlensing searches with Euclid inefficient.

## PREVIOUS NASA-ESA COLLABORATIONS

**Finding:** Previous NASA and ESA collaborations on complementary missions have been successful and mutually beneficial.

Previous ESA and NASA astrophysics missions have often featured an ESA mission followed by a NASA mission, and vice versa. ISO (the Infrared Space Observatory) was followed by SIRTF (later the Spitzer Space Telescope),[35] while XMM (later XMM-Newton) was followed by AXAF (later the Chandra X-ray telescope).[36] Conversely, ESA's Planck mission is now following NASA's WMAP. In the case of XMM-Newton, the small investment of NASA hardware in the ESA mission contributed to the success of that mission and led directly to opportunities for U.S. scientists to participate in the science from that mission. Likewise, U.S. scientist participation in the ISO instrument teams and NASA's contribution of DSN (Deep Space Network) time led to significant opportunities for U.S. scientists using ISO data. Currently, U.S. scientists are contributing about 20-25% of the Planck analysis.[37] In each instance, the later missions have had unique and complementary science capabilities that have led to major new discoveries. In many cases, the involvement of U.S. scientists in earlier ESA missions enhanced the scientific productivity of the later NASA missions.

There is a risk of cost growth associated with any collaboration. NASA's initial involvement in Planck was at the level now proposed for Euclid. It has grown by an order of magnitude and is now comparable to NASA's investment in WMAP.[38] The Implementation Panel rejected a U.S. involvement in Euclid at this higher level.

## DESCRIPTION OF A PROPOSED PLAN FOR A U.S. CONTRIBUTION TO THE ESA EUCLID MISSION

**Finding:** NASA could make modest but important hardware contributions to the Euclid mission.

The discussions between NASA and ESA have identified three specific options for the U.S. hardware contribution to the Euclid mission: near-infrared detector arrays, reaction wheels, or the filter wheel.[39] Corresponding preliminary rough cost estimates provided by NASA to the committee are, in order, $20 million to $25 million, $10 million to $15 million, and $15 million to $20 million (in 2012 U.S. dollars).[40] These are pure hardware costs, without any testing or integration.

U.S. industries are the world leaders in the development and manufacture of NIR detectors. While the expertise in the U.S. academic and laboratory community in testing and integrating NIR detectors for astrophysics missions could be valuable to employ in this context, it would approximately double the cost to NASA.[41]

A U.S. manufactured filter wheel, based on technologies developed for the Hubble Space Telescope, would enable the Euclid telescope to continue its optical observations while the infrared filters are being switched.

Reaction wheels would provide enhanced guiding and stabilization for the Euclid spacecraft, compared with the current mission specification of using cold gas thrusters. This would increase the survey efficiency by reducing slew and settling time. A preliminary estimate indicated an overall increase in survey efficiency of approximately 10 percent.[42]

**Finding:** ESA has offered the United States an opportunity to participate as a partner in Euclid, including membership on the Euclid Science Team. This opportunity would enhance the involvement of the U.S. community in Euclid and improve the ability of the U.S. community to utilize the Euclid data when they become publicly available.

The Euclid science effort is organized into two main bodies: the EST, which currently has 12 members, and the Euclid Consortium, a much larger group comprising more than 900 members from over a dozen countries, with an EC Board as its governing body. The EST includes the Euclid Project Scientist, nine members of the EC Board, and two legacy scientist positions; one of these legacy scientist positions is currently unassigned. The EST is responsible for defining science requirements and is the Euclid scientific advisory body to ESA. The EC is responsible for the visible and infrared instruments on Euclid, data processing, science products, science exploitation, external ancillary data, and simulations.[43] Given the EC's responsibilities, a NASA-appointed position to both the EST and the EC Board (9 of the current 12 EST members have appointments in both[44]) could be important to facilitate the U.S. science return from Euclid.

Previous experience shows that U.S. involvement in science teams has enhanced the U.S. science return from European-led missions.[45] Euclid will release all of its data after its proprietary period—quick-release data will be released 14 months after the start of the survey, and products from all levels will be released 26 months after the start of the survey.[46] If NASA is a partner, it will support making these data available to the U.S. community[47]per NASA policy. With this partnership, U.S. members of the EST and Euclid Consortium members should be able to obtain a deeper understanding of the instrument. This should enhance their ability to carry out analyses of the Euclid data and to combine these data with other surveys.[48]

## PROGRAMMATIC CONSIDERATIONS

**Finding:** NASA has stated that participation in Euclid at the proposed modest level would not delay WFIRST.

NASA presented a plan to the committee for a near-term (fiscal year (FY) 2013-2014) hardware contribution to Euclid with a value of up to $20 million to $30 million (in U.S. dollars). In his presentation to the committee, Astrophysics Division Acting Director Paul Hertz stated that this amount would constitute (and be reallocated from) about 20 percent of the funds planned within the run-out of the president's FY2012 budget request for allocation by the division for NWNH priorities in the same timeframe and would thus have a modest albeit non-negligible impact on those programs. Dr. Hertz also stated that expenditure of these funds on Euclid hardware would not impact the launch schedule for WFIRST, since according to current NASA budget projections significant expenditure on the WFIRST mission would only commence in the 2017-2018 timeframe, when JWST construction spending rolls off. As part of its participation in Euclid, NASA would also support a science team at the $1.5- to $3-million-per-year level expected in the 2016-2025 timeframe.[49]

**Finding:** Despite its priority in NWNH, WFIRST has only very low-level support for pre-phase-A studies.

While WFIRST does not present major technical challenges, thorough mission studies would enable the mission to move forward quickly once funding is available. WFIRST lacks any grants program that supports mission studies (such as scientific mission simulations) outside the U.S. NASA centers.[50]

# 3
# Conclusions and Recommendations

**CONCLUSION: U.S. participation in Euclid would represent a valuable first step toward meeting one of the science goals (furthering dark energy research) of NWNH for WFIRST. However, Euclid on its own does not provide a viable alternative for achieving the broader NWNH goals for the WFIRST mission, nor does it achieve the more ambitious goals for WFIRST's dark energy measurements.**

Euclid will carry out an exciting science program that should yield important scientific results. Benefits of U.S. participation in the Euclid Consortium should also include detailed knowledge of, experience with, and access to Euclid instruments, data pipelines and products, simulations, and modeling, and most importantly, opportunities for U.S. scientists to participate fully in this promising mission. This knowledge could help optimize the science return of the WFIRST mission as well. Such an investment will further the goals of NWNH, be helpful to the preparations for WFIRST, and enhance WFIRST's chances of success. The committee reached this conclusion that a U.S. role in Euclid would be beneficial to U.S. science, although as NWNH concluded and as the committee heard in evidence presented by several experts, Euclid cannot carry out the full science priorities envisioned in NWNH.

WFIRST will uniquely carry out the important NWNH goals of exoplanet studies and a guest observer program.[51] Moreover, the presentations to the committee that offered direct comparison of Euclid and WFIRST capabilities for dark energy research showed clear advantages of WFIRST for both the galaxy clustering (baryon acoustic oscillation, BAO) and weak gravitational lensing techniques that make up the Euclid mission. In addition, WFIRST includes the supernova technique whose demonstrated, well-characterized performance serves as an important complement to BAO and weak gravitational lensing. When combined with the results of the Kepler mission, WFIRST's gravitational microlensing planet search will produce a comprehensive demographic survey running from Mercury-scale orbits to beyond the snow line in hundreds of exo-solar systems, data that will provide an essential observational constraint on the physics of planet formation. The remarkable potential of a deep multiband, near-infrared galaxy survey over a large fraction of the sky and a stellar survey covering the galactic plane and halo will go unrealized without WFIRST. These near-infrared surveys should deliver significant science benefit to multiple areas of astronomy. WFIRST's observations in Guest Observer mode will, for example, invigorate studies of stellar evolution, providing precise ages for star clusters and an infrared probe of the most vigorous sites of star formation in our Galaxy and its neighbors.

**RECOMMENDATION: NASA should make a hardware contribution of approximately $20 million to the Euclid mission to enable U.S. participation. This investment should be made in the context of a strong U.S. commitment to move forward with the full implementation of WFIRST in order to fully realize the decadal science priorities of the NWNH report.**

**RECOMMENDATION: In exchange for this small, but crucial, contribution, NASA should secure through negotiation with the European Space Agency both a U.S. position on the Euclid Science Team with full data access and the inclusion of a team of U.S. scientists in the Euclid Consortium that would be selected by a peer-reviewed process with full data access as well as authorship rights consistent with Euclid policies still to be formulated.**

As with all NASA missions, the expectation is that NASA will ensure and support access to the Euclid data for the wider U.S. community once the proprietary data period has expired. This involvement is especially important for Euclid, whose survey data should enable significant legacy science. Through its direct involvement in Euclid, the U.S. science team will enhance not only the U.S. capabilities to study dark energy but also the broader use of the Euclid data by the U.S. community. If software developed by the U.S. Euclid team is made available to the community when the Euclid data become public, this step also will enhance the broader community's ability to use the Euclid data. While the U.S. role on the EST should be more carefully delineated through negotiations with the European Space Agency, it could, for example, involve leadership in Euclid legacy science, defined as providing value-added data products to the community that combine relevant ground and space data sets (including those from WFIRST), given the importance of data dissemination to the U.S. community.

NASA and the European Space Agency are discussing several possible options for the U.S. hardware contribution. While the two agencies should determine the nature of the U.S. contribution, contributions with the maximum science benefit to the Euclid mission will benefit both the European and the U.S. communities.[52] The reaction wheel could offer a significant improvement in mission efficiency. The filter wheel would also provide some benefit to the mission and would take advantage of U.S. expertise in designing filter wheels (e.g., for the Hubble Space Telescope). The near-infrared detectors, if characterized by U.S. instrumentalists who have expertise in this area, would be beneficial but would likely be the more expensive of the options.

The science goals of WFIRST go far beyond those of Euclid, and WFIRST is central to realizing those goals and to maintaining U.S. leadership in astronomy and astrophysics in the next decade and beyond. The committee notes that early expenditures on pre-phase A studies, particularly those that engage the community, often accelerate mission timelines and reduce costs.

Mission collaboration costs often grow, as demonstrated by the U.S. participation in the Planck mission discussed above. The committee recommends a tripwire for the hardware costs at 50 percent above the recommended value of $20 million.

**RECOMMENDATION: NASA should seek independent community review of any financial commitment for hardware expenditures beyond $30 million for Euclid.**

The committee recognizes that support for this science team will cost an additional ~$2 million per year for about 10 years, for a total that is similar to the hardware investment. That is a necessary expense and not the kind of increase discussed herein. Given the constraints on the NASA budget it is crucial that the contribution to Euclid not grow and impact the rest of the space astrophysics program. The Decadal Survey Implementation Advisory Committee (DSIAC) proposed and described in NWNH would provide an appropriate mechanism for such a review.

**CONCLUSION: The committee concludes that the combination of data from planned U.S.-led ground-based surveys with Euclid and WFIRST data will enhance the science return from both the ground- and space-based surveys, and that a coordinated, strategic approach to managing these joint data sets could position the U.S. community for a leadership role in their scientific exploitation.**

The necessity of ground-based data to Euclid's scientific success provides a potential basis for negotiating agreements between the ground-based projects and the Euclid mission, which could lead to increased U.S. scientific participation in Euclid. The Department of Energy and the National Science Foundation are the predominant sources of support for two of the U.S.-led ground-based projects, the Dark Energy Survey and the Large Synoptic Survey Telescope. The degree to which these agreements might be coordinated with the proposed NASA participation in Euclid is a matter that the Astronomy and Astrophysics Advisory Committee, which is charged with considering interagency issues, could consider.

Obtaining the full scientific benefits of the combined ground- and space-based data will likely require joint processing and analyses of the combined data sets at the pixel level. This deep level of engagement in the data argues for direct collaboration between the ground- and space-based projects. Such joint analyses would require significant data management resources that are not currently budgeted within these projects.

## Notes

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44. Yannick Mellier, Institut d'Astrophysique de Paris, "Euclid: Mapping the Geometry of the Dark Universe," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 18, 2012.

45. George Helou, California Institute of Technology, "Lessons Learned from Past and Current NASA-ESA Collaborations," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 19, 2012.

46. Yannick Mellier, Institut d'Astrophysique de Paris, "Euclid: Mapping the Geometry of the Dark Universe," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 18, 2012.

47. Paul Hertz, NASA, "Panel Discussion with NASA," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 18, 2012.

48. Chris Hirata, California Institute of Technology, "Discussion of Euclid and WFIRST Gravitational Lensing Capabilities," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 19, 2012.

49. Paul Hertz, NASA, "Panel Discussion with NASA," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 18, 2012.

50. The committee notes that, as of January 20, 2012, the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES) system does not list any such program.

51. NRC, *New Worlds, New Horizons in Astronomy and Astrophysics,* 2010, p. 208.

52. Jason Rhodes, Jet Propulsion Laboratory, "U.S. Perspective on a U.S. Contribution to Euclid," presentation to the Committee on the Assessment of a Plan for U.S. Participation in Euclid, National Research Council, Washington, D.C., January 19, 2012.

# Appendixes

# A
# Statement of Task

The NRC will organize an ad hoc study to determine whether a proposed NASA plan for a U.S. hardware contribution to the European Space Agency (ESA) Euclid mission, in exchange for U.S. membership on the Euclid Science Team and science data access, is a viable part of an overall strategy to pursue the science goals (dark energy measurements, exoplanet detection, and infrared survey science) of the New Worlds, New Horizons report's top-ranked, large-scale, space-based priority: the Wide Field Infrared Survey Telescope (WFIRST).

# B
# Meeting Agenda

### JANUARY 18, 2012

### Closed Session

| | | |
|---|---|---|
| 9:00 a.m. | Welcome and Plans for the Meeting | David Spergel, Chair |

### Open Session

| | | |
|---|---|---|
| 9:30 | Welcome and Plans for the Meeting | David Spergel, Chair |
| 9:35 | NASA discussion of a plan for U.S. Participation in Euclid | Waleed Abdalati, NASA |
| | *Discussion* | |
| 10:35 | Panel Discussion with NASA | Paul Hertz, Acting Director, Astrophysics Division<br>Richard Griffiths, Euclid Program Scientist<br>Rita Sambruna, WFIRST Program Scientist<br>Lia LaPiana, Euclid and WFIRST Program Executive |
| 11:30 | ESA Perspective on a Plan for U.S. Participation in Euclid (via videoconference) | Fabio Favata, ESA |
| 12:20 p.m. | The Euclid Mission (via videoconference) | Yannick Mellier,<br>Institut d'Astrophysique de Paris |
| 12:55 | *Discussion with ESA and Euclid Representatives* | |
| 1:45 | U.S. Perspective on a U.S. Contribution to Euclid | Jason Rhodes,<br>Jet Propulsion Laboratory |
| | *Discussion* | |
| 2:20 | Discussion of WFIRST and Euclid | Paul Schechter,<br>Massachusetts Institute of Technology |
| | *Discussion* | |

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|---|---|---|
| 3:15 | Discussion of LSST, WFIRST, and Euclid | Steve Kahn, Stanford University |
| | *Discussion* | |
| 3:50 | Discussion of Ground- and Space-Based Dark Energy Missions (via videoconference) | David Weinberg, Ohio State University |
| | *Discussion* | |
| 4:25 | Discussion of the Current Study in the Context of *New Worlds, New Horizons* | Roger Blandford, Stanford University |
| | *Discussion* | |
| 5:05 | Discussion of the Current Study in the Context of the Implementation Panel Report (via teleconference) | Adam Burrows, Princeton University |
| | *Discussion* | |

**Closed Session**

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| 5:40 | Committee Discussion |
| 6:45 | Working Committee Dinner |
| 8:30 | Adjourn for the Day |

**JANUARY 19, 2012**

**Closed Session**

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| 8:00 a.m. | Breakfast and Discussion of Previous Days' Talks | Committee |

**Open Session**

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|---|---|---|
| 9:00 | WFIRST and Euclid impact on dark energy research | Michael Turner, University of Chicago |
| | *Discussion* | |
| 9:40 | Discussion of Euclid and WFIRST Gravitational Lensing Capabilities (via WebEx) | Chris Hirata, California Institute of Technology |
| | *Discussion* | |
| 10:10 | Discussion of WFIRST and Euclid exoplanet microlensing | Dave Bennett, University of Notre Dame |
| | *Discussion* | |

| | | |
|---|---|---|
| 10:45 | Impact of Current and Future Developments in Microlensing on Euclid and WFIRST (via WebEx) | Dimitar Sasselov, Harvard University |
| | *Discussion* | |
| 11:20 | Lessons Learned from Similar Past NASA-ESA Collaborations | George Helou, California Institute of Technology |
| | *Discussion* | |
| 11:55 | Public Comment Session | |

**Closed Session**

12:15 p.m. Committee Discussions

**Open Session**

| | | |
|---|---|---|
| 2:30 | Panel Discussion with NASA | Paul Hertz, NASA Astrophysics Division |

**Closed Session**

3:50 Committee Discussion

6:00 Adjourn for the Day

**JANUARY 20, 2012**

**Closed Session**

8:00 a.m. Committee Discussions

3:00 p.m. Adjourn Meeting

# C
# Meeting Presentations and Open Session Summaries

The Committee on the Assessment of a Plan for U.S. Participation in Euclid held a meeting on January 18-20, 2012, at which a number of presentations were made as described in Appendix B. Below is a brief overview of the presentations made at the committee's meeting. In order to help focus the presentations and in the interest of efficient data gathering, the committee prepared guiding questions that were delivered to the speakers prior to the meeting. These questions are reproduced below, alongside a short summary of each speaker's presentation. Additional questions not listed below were asked during the actual meeting. Speakers' viewgraphs are available, as provided, on request through the National Research Council's (NRC's) Public Access Records Office.[1]

## DAY 1—JANUARY 18, 2012

### NASA Discussion of a Plan for U.S. Participation in Euclid

*Speaker: Waleed Abdalati, NASA Chief Scientist*

**Guiding Questions**

1. What does NASA propose to provide to ESA?
2. Would this commitment likely to grow over the mission?
3. What data access will the U.S. community acquire?
4. What would be the potential U.S. role on the Euclid science team? How would U.S. participants be selected?
5. What are possible connections between Euclid and WFIRST enabled by a NASA commitment?
6. What are the current plans for implementing the NWNH recommendation on WFIRST? If they do plan to implement, what schedule, cost, scope do they currently envision, given the current budget situation, JWST, etc.? How might NASA investment in Euclid impact the WFIRST mission with respect to science goals, instrumentation, cost, and schedule?
7. How would a NASA investment in Euclid be coordinated with potential sharing of data from U.S. ground based DE projects, in particular, DES, PanSTARRS, and LSST?
8. Would a NASA investment in Euclid be likely to lead to an ESA investment in WFIRST?
9. What is the impact of NASA participation in Euclid on the Explorer program?
10. How would Euclid instrumentation be altered if United States did not participate?
11. How is U.S. data access affected by U.S. participation or non-participation?

[1] The Public Access Records Office provides access to project materials available to the public, and can be accessed via the Current Projects System at http://www8.nationalacademies.org/cp/.

12. What will not get done at NASA if this money is spent on Euclid?
13. What chance is there that WFIRST will not be done at all, with or without Euclid?

**Session Summary**

Waleed Abdalati delivered an overview for the study to Assess U.S. Participation in Euclid. He began with the current status of the WFIRST mission. JWST has been designated as the first funding priority for NASA Astrophysics with a launch date for WFIRST no earlier than 2022. Abdalati cautioned that this was a highly ambitious launch date due to the current budget situation. He continued on to discuss previous NASA contributions to foreign missions and the current opportunity for U.S. participation in the ESA Euclid mission, which is scheduled to launch in 2019. The contribution being discussed was a hardware contribution, possibly in the form of one of the following: near-infrared (NIR) detectors, a filter wheel for the NISP instrument, or reaction wheels. In return, NASA would receive one position on the Euclid Science Team (EST) with accompanying co-collaborators becoming members of the Euclid Consortium (EC). NASA would also receive immediate access to the Euclid data, as opposed to waiting until the end of the proprietary period. In addition, this would set the stage for discussions of future collaborations on software development for Euclid as well as European collaborations on WFIRST—although neither of these are under discussion at this time. Abdalati stated that a formal commitment from NASA to ESA would be necessary by Spring 2012. Abdalati stated that the $20 million to $25 million cost of the hardware contribution to Euclid would have no impact on WFIRST since the project is not likely to begin within the next few years. When asked about possible coordination with other U.S. agencies, such as the Department of Energy, he stated that there are no collaborations in the works at the moment, but this could be a possibility in the future.

## Panel Discussion with NASA Summary

*Panelists: Paul Hertz (Acting Director, Astrophysics Division), Richard Griffiths (Euclid Program Scientist), Rita Sambruna (WFIRST Program Scientist), Lia LaPiana (Euclid and WFIRST Program Executive)*

Representatives from NASA participated in a panel discussion with the committee to offer insight into the proposed agreement with ESA concerning a hardware contribution to the Euclid program. Building on Waleed Abdalati's earlier presentation and answering questions from the committee, the NASA panel outlined more details of the expected terms of an agreement with NASA—that is, a hardware contribution in exchange for a seat on the EST and immediate access to the data. They stressed that the deal would be neither a quid pro quo nor a package deal with a potential future NASA-ESA collaboration on WFIRST. A separate discussion of ESA's potential participation in WFIRST would come at a later time. Hertz discussed the potential effects on WFIRST, financial and otherwise, assuring the committee that although there would be some cost constraints associated with participation in Euclid, this would not hinder the WFIRST schedule. He confirmed that there would also be costs in the out years to support a science team, but these would most likely be traded with other opportunities in the astrophysics budget. Owing to the costs of completing JWST, the current expectation for the budget does not have an opening for WFIRST until 2018, with a launch date of 2022 or later. The committee questioned whether the proposed $20 million for Euclid could instead be used to accelerate WFIRST. The NASA panel responded that while $20 million is a significant amount of money, Phase B of WFIRST is easily $100 million per year, so this current Euclid plan would not considerably impact the ramp-up phase of WFIRST when it occurs.

## ESA Perspective on a Plan for U.S. Participation in Euclid

*Speaker: Fabio Favata, Head of ESA's Science Planning and Community Coordination Office*

**Guiding Questions**

1. What is the U.S. contribution to Euclid discussed with NASA? Is it likely to grow? What are the consequences of the United States not joining Euclid?
2. What would be the U.S. role on the Science Team? What is the Management structure of Euclid? How would the United States fit into this structure?
3. What is the potential ESA role in a WFIRST mission?
4. What is the current Euclid schedule?
5. What are the major technical, cost and schedule risks in the Euclid mission? Does NASA participation reduce these risks?

**Session Summary**

Fabio Favata delivered a presentation to the committee concerning U.S. participation in the ESA Euclid program. Favata began by explaining the organization and budget of ESA. He continued on to the role of the United States, which would consist of a hardware contribution in the form of NIR detectors, a filter wheel for NIR instruments, reaction wheels, or a contribution to the science ground segment. In exchange, the United States would receive one seat on the Euclid Science Team (EST) and a guaranteed "10 percent" science return which would be measured by the number of first authorships or by other alternative metrics as agreed upon by the EST. The Euclid management structure includes the Euclid Consortium (EC), which is responsible for scientific exploitation of the data, and the EST, which manages the program and proposes program elements. Favata elaborated on the current schedule for Euclid, stating that a 7-year development period is foreseen with no major risks compared to other Soyuz-class ESA astronomical missions. The mission is currently approved as a "European-only" mission; however, U.S. participation would be welcome. As far as WFIRST and Euclid are concerned, Favata noted that the two missions are decoupled and in very different stages. ESA would be happy to discuss possible collaborations on WFIRST once the mission is defined and approved.

## The Euclid Mission

*Speaker: Yannick Mellier, Institut d'Astrophysique de Paris; Spokesperson for the Euclid Consortium*

**Guiding Questions**

1. What are Euclid capabilities for measuring dark energy?
2. Describe Euclid's capabilities in the following four areas:
    a. Gravitational Lensing
    b. BAO
    c. Microlensing
    d. Infrared Surveys
3. Would the Euclid team be open to making surveys and microlensing part of its core mission?
4. What is the role of ground-based missions in the Euclid analysis? Please discuss the likely role of DES, panSTARRS and LSST? How accurately will Euclid need to characterize the color gradients?
5. What are the Euclid plans for data release?

6. What would be the U.S. role on the Science Team? What is the scientific Management structure of Euclid? How would U.S. scientists fit into this structure?

7. What do you see as the scientific relationship between Euclid and WFIRST?

**Session Summary**

Yannick Mellier gave a follow-up presentation complementing information discussed by Fabio Favata. Mellier began with Euclid's capabilities for measuring dark energy, distinguished by using two independent techniques—the geometry of the universe and the history of structure formation. Weak lensing (WL) and galaxy clustering would be used to study the geometry of the universe while WL, redshift-space distortion (RSD), and clusters of galaxies would be used for information on the cosmic history of structure formation. Minimizing and controlling systematics will be done with an unprecedented level of accuracy. Euclid will include an instrument for VIS (one wavelength wide field, high image quality) and two for NISP (one wide field NIR with Y, J, and H filters for photo-z, and one wide-field NIR slitless spectrograph for spectroscopic redshifts). Dark energy probes include cosmic shear weak lensing tomography, baryon acoustic oscillation (BAO), clusters of galaxies, RSD, and ISW. Mellier also discussed the role of ground-based missions. He noted a need for photometric redshifts for all sources used for WL as well as a need for spectra to calibrate photometric redshifts. Mellier noted that there has been some interest in using results from Pan-STARRS to assist in northern sky coverage; however, there is some uncertainty pertaining to the Pan-STARRS2 project at the moment. He envisioned the cost for coordinating with Pan-STARRS being between $15 million to $19 million.

Mellier then described Euclid's capabilities for microlensing and infrared surveys and the willingness to include this as part of their core mission. The NISP instrument is capable of $0.54^{\circ 2}$, Y, J, and H photometry for microlensing and infrared surveys, and there is also possible low-resolution slitless spectroscopy specifically for infrared surveys. He stated that the instrument is capable of keeping the same target for 1 month and can cover very wide fields. The Euclid Consortium (EC) is interested in expanding the program to include microlensing and NIR as well as supernovae, but not at the expense of the core cosmology program. He did suggest that this could later become a possibility if the mission were to be extended.

An outline of the Euclid management structure and U.S. contribution was discussed next. Mellier stated that there are currently more than 900 registered members of the EC. The EC is responsible for the science requirements and goals, instrument maintenance and operation, data exploitation and processing, and any external ancillary data to achieve the mission's scientific goals. The EC Board (ECB) acts as the governing body of the EC and contains 18 full members from Europe and would have 2 at-large members without voting privileges from the United States. The EST is the only Euclid scientific advisory body and currently has 9 members. Mellier noted that possible U.S. contributions include hardware, ground observations, and science. In return, the United States would hold a seat on the EST with possible expertise in weak lensing or NIR plus a possibility of 1-2 members of the ECB and guaranteed science return. The terms of the science return would be further determined by the EST. When questioned about the need for a representative on the ECB, Mellier said it was the best way to interact with the consortium, but not absolutely necessary. With respect to plans for data release, he said that the data would be immediately available to the United States as it would any other EST member. For the outside community, level Q (quick-release) data would be released 14 months after the start of the survey, and products from all levels would be released 26 months after the start of the survey.

Mellier discussed the current Euclid timeline, scheduled to begin the Implementation phase in the fourth quarter of 2012. PDR would follow in the third and fourth quarters of 2013 with structural and thermal delivery in the first quarter of 2014, electrical model delivery in the third quarter of 2014, flight model delivery in the third and fourth quarter of 2017, and finally the launch in the fourth quarter of 2019. Concerning the relationship between WFIRST and Euclid, he remarked that they are complementary—Euclid is designed for wide sky coverage and deep surveys of extragalactic sky while WFIRST is

optimized for microlensing surveys, Type 1a supernovae surveys, and ultra-deep surveys of extragalactic sky and, possibly, of the galactic plane.

The committee questioned if LSST data would be used. Mellier responded saying that from the Euclid side, the data would be useful for photometric redshift, but was not positive it was necessary for the Southern sky.

There was some discussion on the importance of color gradients in WL studies to which Mellier noted that this is not a problem on Euclid because the VIS instrument is equipped by two identical narrow band filters and just one filter is sufficient to observe many more galaxies than needed to correct color gradient effects. He also noted that a working group has been established to study color gradient effects and this working group has demonstrated that there is no need for another (third) filter different from the narrow band filters already put on VIS instrument.

## U.S. Perspective on a U.S. Contribution to Euclid

*Speaker: Jason Rhodes, Jet Propulsion Laboratory; member of the Euclid Consortium (EC), non-voting member of the EC Board, member of the WFIRST science definition team*

### Guiding Questions

1. What do you see as the U.S. contribution to Euclid? Is it likely to grow?
2. What would be the U.S. role on the Science Team?
3. What are the Euclid plans for data release?
4. What do you see as the relationship between Euclid and WFIRST?
5. What do you see as the relationship between Euclid and various U.S.-led ground-based surveys?
6. What do you see as the relationship between Euclid, WFIRST, and the goals of the decadal survey?

### Session Summary

Jason Rhodes gave a presentation to the committee on the potential U.S. contribution to Euclid from a U.S. perspective. Rhodes began by stating that the U.S. contribution would likely be in the form of hardware such as reaction wheels, NIR detectors, or detector performance validation for weak lensing. There is also the possibility of a contribution to the processing/ground segment as well as the science. In return, the United States could expect to receive one seat on the EST and a 10 percent science return. Rhodes remarked that the presence of a U.S. member on the EST would be important to safeguard U.S. interests and also to facilitate Euclid's tapping into U.S. expertise and resources. The member would participate in all EST activities, with possible additional duties depending on their expertise. He noted that this member should, but is not required to, integrate personnel and U.S. science efforts with the EC and become fully engaged in the science exploitation of the data. In terms of data release, Rhodes said the members of the U.S. community that are involved in the Euclid Consortium (via joining the science team NASA would support) are the only members of the U.S. community that would have immediate access to data. This is the same as in Europe—EC members have immediate access. All outside parties would have to wait the duration of the proprietary period, which would be 14 months for quick data and 26 months for full data, with subsequent yearly releases.

Rhodes also discussed the relationship between Euclid and WFIRST, noting that they should be largely complementary. Independent, complementary approaches would not only be desirable but necessary in order to accomplish the goals outlined in the NWNH decadal survey. He stated that a phased approach to implementing Euclid and WFIRST could prove beneficial, with WFIRST benefitting from

early Euclid observations. With regard to Euclid and U.S.-led ground-based surveys, Rhodes stressed that ground-based data would be required over the entire survey area for photo-z's as well as ground-based spectra for calibration. Finally, he commented that the United States is capable of leadership in all aspects of Euclid science, but competition is not beneficial. He believed that shared leadership should be sought and coordination with the EC would be ideal. When questioned how amenable ESA would be to a U.S. influx into the working groups, Rhodes suggested it might take a little bit of work and patience, but no more so than when the groups were originally formed.

## Discussion of WFIRST and Euclid

*Speaker: Paul Schechter, Massachusetts Institute of Technology; Co-Chair of NASA's WFIRST Science Definition Team*

**Guiding Questions**

1. What is your assessment of Euclid ability to address the scientific goals of the decadal survey? Will the U.S. contribution affect its capabilities?
2. Can you compare and contrast Euclid and WFIRST?
3. What is the current status of WFIRST planning?
4. How does the planned launch of Euclid affect plans for WFIRST? Does the infrared contribution alter this relation?

**Session Summary**

Paul Schechter discussed the Euclid and WFIRST missions. Schechter began with the current status of WFIRST, remarking that if the mission got a "new start" in 2013, it would be possible to launch by 2020 and that any slippage will be the result of budgetary rather than technical considerations. When comparing the two programs, he noted that Euclid's science program does not include exoplanet microlensing, a guest observer program, and supernovae dark energy measurements. By contrast, the current design reference mission for WFIRST includes all of the science objectives mandated by the NWNH decadal survey. Euclid devotes 6.25 years to BAO plus weak lensing as opposed to 2 years for WFIRST. Schechter noted that Euclid uses an obstructed telescope, while WFIRST will use an unobstructed telescope. He also remarked that WFIRST is preferred for weak lensing, which will be the riskiest program. Schechter argued that that the BAO programs of both missions are comparable. He also said that if WFIRST did not get a new start in 2013, the added year might be productively used to bring the next generation of infrared detector, called "Hawaii-4RG" up to the required technical readiness level, enhancing the capabilities of WFIRST by somewhere between 50 and 100 percent.

## Discussion of LSST, WFIRST, and Euclid

*Spaker: Steve Kahn, Stanford University; Deputy Project Director and Camera Lead Scientist for the LSST project*

**Guiding Questions**

1. Do you see the Euclid data as useful for LSST analysis?
2. Do you see the LSST data as useful for Euclid analysis?
3. What are the plans for LSST data release?

4. What is the current LSST schedule?
5. What do you see as the scientific synergies between LSST and WFIRST?
6. What do you see as the relationship between Euclid, WFIRST, and the goals of the decadal survey?

**Session Summary**

Steve Kahn delivered a discussion of the LSST, WFIRST, and Euclid missions and the potential relationships among the three. He began by stating that the Euclid data would benefit LSST in a number of ways. The Y, J, and H color information would produce a modest improvement in the photo-z determination, the spectroscopic survey would help calibrate and understand photo-z systematics, and a comparison of the shear determinations will assist in constraining and understanding shape measurement systematics. Kahn also believed LSST is crucial to Euclid, since Euclid requires multicolor visible band photometry in the Southern Hemisphere, and LSST will be the premier facility to deliver such data. LSST will go deeper than Euclid, while covering a comparable fraction of the sky. He continued on to discuss the plans for LSST data release that will be processed annually to produce calibrated images and a catalog of detected sources and their measured properties. Processed data will be released publicly to the U.S. and Chilean communities as well as select foreign partners. With respect to Euclid, Kahn recommended that the United States and ESA should negotiate over the use of LSST data for Euclid analyses. He then provided a complete schedule for LSST, including milestones for the National Science Foundation, the Department of Energy, and private-sponsored endeavors.

Moving on to LSST and WFIRST, Kahn emphasized several areas in which the two missions are complementary. LSST will be a synoptic, time-dependent survey of half the sky in the visible band. WFIRST will be a more detail-targeted survey for distinct scientific missions in the NIR. LSST will is purely an imaging facility, while WFIRST will incorporate imaging and spectroscopic survey capabilities. He stressed that both will contribute significantly to dark energy science. When addressing Euclid, WFIRST, and the NWNH decadal survey, Kahn felt that the two missions offer complementary capabilities that will further the goals set forth in the survey. To conclude, he noted that a tight collaboration between Euclid and LSST will be necessary to ensure a common strategy in the derivation of the photometry in the visible and NIR bands. Since the LSST data will require a reanalysis to facilitate any collaboration, Kahn suggested that the provision of LSST data be a key component of any proposed U.S. contribution to Euclid.

## Discussion of Ground- and Space-Based Dark Energy

*Speaker: David Weinberg, Ohio State University; Former Vice-Chair of the Astro2010 Science Frontiers Panel on Cosmology and Fundamental Physics; member of BOSS (SDSS-III Project Scientist); member of the Dark Energy Survey collaboration; member of the BigBOSS collaboration*

**Guiding Questions**

1. Please discuss the likely capabilities of ground-based projects (BigBOSS, point spread function, eBOSS, etc.), compare to the likely capabilities of Euclid and WFIRST?
2. Do you see the Euclid observations as complementary to the WFIRST measurements or likely to eliminate the need for space-based BAO observations? How is this affected by a U.S. contribution?

**Session Summary**

David Weinberg gave a discussion on ground- and space-based dark energy facilities and began with an overview of a fiducial stage IV program,[2] including supernovae, baryon acoustic oscillations (BAO), weak lensing (WL), and cosmic microwave background. Weinberg stated that ground-based galaxy BAO surveys will do well out to $z \approx 1.0$ to 1.2 and for $z = 2$ to 3 from the Ly$\alpha$ forest. However, he noted that the low-infrared background from space is an immense advantage for observing over $z = 1$ to 2. He felt that the ground would make a start in this z-range but would be unlikely to compete with space, unless radio intensity mapping proved to be a feasible possibility. As a result, Euclid and WFIRST would offer access to precision BAO and redshift space distortion in a range inaccessible from the ground. Weinberg then discussed the planned observations of Euclid as compared to WFIRST. The baseline plans currently show that WFIRST would perform a factor of two better than Euclid in wide survey mode and would be much better in deep mode. He believed that observations from the two missions could easily be arranged to be complementary. In conclusion, he stated that the United States has a strong interest in the scientific success of Euclid and in ensuring timely and effective dissemination of Euclid data. He also noted that giving top U.S. WL experts a role in Euclid would help Euclid and WFIRST and LSST. When questioned how he felt about giving up BAO on WFIRST, Weinberg said that if the impact on the other WFIRST observing programs were equal, then he thought there would be as good an argument for giving up weak lensing as for giving up BAO.

## Discussion of the Current Study in the Context of New Worlds, New Horizons

*Speaker: Roger Blandford, Stanford University; Chair of the NRC's 2010 Astronomy and Astrophysics Decadal Survey (Astro2010) that produced New Worlds, New Horizons in Astronomy and Astrophysics*

**Guiding Questions**

1. Based on the decadal survey and the implementation report, what are your recommendations for the committee's charge?
2. How would U.S. participation in Euclid as a minor partner address the goals and priorities of NWNH?

**Session Summary**

Roger Blandford reviewed the task of the Astro2010 decadal survey and the recommendations of the NWNH report. He reminded the committee that NWNH made recommendations for two budget scenarios, and he noted that the reality of the budget climate now is worse than the pessimistic NWNH scenario. He said that the WFIRST program as currently envisioned remains true to the scientific program laid out in NWNH, and he reminded the committee that WFIRST is the top large space-based priority, while noting it was not ranked against the medium and small recommendations. He said the NWNH statement that the United States play a leading role was carefully chosen, in that the committee did not intend that the United States lead any joint ESA-NASA collaboration alone (the leading role, versus a leading role).

Blandford gave a brief update of the status of the NWNH recommendations and agency actions since the report release in August 2010. He noted that NASA has created a science definition team for WFIRST, the Explorer Program funding is being increased, and the U.S. teams for IXO and LISA were

[2] Stage IV program is defined on page 2 of the AAAC Dark Energy Task Force Report as "major, long-term projects."

disbanded. Since then, ESA has decided to pursue x-ray and gravitational-wave missions without U.S. support. He said that NASA's astrophysics discoveries have been remarkable, and he noted several upcoming Explorer program missions.

In response to the first questions asked, Blandford said that the kind of U.S. participation in Euclid, with the United States as a minor partner as described by NASA and ESA at this meeting, would give quick access to the data for the U.S. science team. He noted that that it was implicit in NWNH that the United States would be a leader in executing the science of WFIRST. He also said that the United States could significantly impact the Euclid mission by means of scientific and hardware contributions. He noted that a micro-lensing survey is proposed with the Euclid satellite was possible after about 6 years when the cosmology survey is finished. Responding to further questions, Blandford said that while he could not speak for the Astro2010 survey committee since the current scenario was not discussed in the preparation of the survey report, his personal view is that, given the financial situation, the United States should engage in Euclid as proposed, along with continuing to develop WFIRST. Going forward, he said it will be vital to ask the NRC's Committee on Astronomy and Astrophysics to review any future escalation of the commitment and to advise on the balance against WFIRST development, the Explorer program, NASA's program of smaller activities, technology development, and the other NWNH recommendations.

## Discussion of the Current Study in the Context of the "Implementation" Panel Report

*Speaker: Adam Burrows, Princeton University; Former Co-Chair, with Charles Kennel, of the NRC's Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey*

### Guiding Questions

1. Based on the decadal survey and the implementation report, what are your recommendations for the committee's charge?
2. How would U.S. participation in Euclid as a minor partner address the goals and priorities of NWNH?

### Session Summary

Adam Burrows opened his discussion reviewing the history that brought about the NRC Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey (the Implementation Panel)—which was convened in November 2010 to consider an earlier proposal for U.S. participation in Euclid. Burrows noted that in September 2010, following the prepublication release NWNH in August 2010, the White House's Office of Science and Technology Policy requested a short study on whether a proposed NASA 20-percent share in Euclid was consistent with NWNH recommendations. He said that the task of the panel he co-chaired was not to review or revise the Astro2010 survey, but instead it was tasked to focus on the question of whether the proposed 20-percent investment in Euclid was consistent with accomplishing the recommendations of NWNH. The panel concluded that the proposed contribution was not consistent with the recommendations of NWNH. The panel also considered three other options for U.S. participation in Euclid. Burrows described the four options the panel report laid out: the launch of WFIRST in the decade 2012-2021, a joint WFIRST/Euclid mission, commitment by NASA of 20-percent investment in Euclid prior to the M-class decision, or no U.S. financing of an infrared survey mission this decade.

Burrows said that the panel was cognizant of the wording in NWNH about the United States having a leading role in fulfilling the WFIRST science capabilities. He said that the Implementation Panel concluded that the Euclid mission would only address one of the WFIRST science goals and that an

investment in Euclid might cause an imbalance in the survey's recommended strategy. He noted that NWNH did not rank specific science goals or prioritize between large-, medium-, and small-scale activities and that the survey emphasized the need for balance across all scales of activities. In response to the questions asked by the committee, Burrows said that it seems the current proposal from NASA is similar to the Implementation Panel's second option—a joint Euclid-WFIRST mission—with the difference that instead of a joint mission there could be an overall joint science effort toward achieving the WFIRST science goals by pursuing both missions.

He said that having a Decadal Survey Implementation Advisory Committee (DSIAC), as recommended by NWNH to monitor the survey's recommendations, is all the more important in the current budget situation. When asked about the language about the United States being a leader in any joint mission, Burrows elaborated that the Implementation Panel felt that U.S. scientists should have full access to data—that the United States would need to archive—and that the United States should be involved in planning, but that the contribution does not necessarily need to be dominant.

### Final Discussion Summary

The final discussions from the first day centered on possible hidden costs in the current proposal for a $20 million hardware contribution. Paul Hertz from NASA was asked about clarifying the cost of the hardware contributions under consideration and for information on what the cost for supporting a U.S. Euclid Science Team would be, and Hertz offered to prepare a response to be discussed during the discussion on the second day of the meeting. Hertz reminded the committee that these additional costs would not be included in the current proposal, and future involvement would be decided as those issues arose later. Additionally, Hertz said that a U.S. Euclid Science Team would not be a full-time group, which would limit the associated costs.

Jason Rhodes, Jet Propulsion Laboratory, volunteered that, in his experience with a NASA-funded science team, the cost for a group of about 20 members over 11 or 12 years was about $30 million, including several senior principal investigators. Another issue raised was the need for funding for LSST to adapt to complement the Euclid surveys, but it was noted that NASA does not support LSST or the Dark Energy Survey (DES). It was noted in the discussion that funding would also be needed for Euclid data archiving. The discussion also touched on the issue of a commercial procurement for an infrared detector, and Hertz noted that ESA has only asked for the detectors directly from Teledyne with no other U.S. characterization or testing. Hertz continued noting that if the United States wanted to characterize or supply electronics that would cost more than the $20 million currently being considered, he would look into those costs and try to prepare an answer for the committee to discuss on the second day. Hertz also noted that NASA make its contribution in the form procuring the infrared detector. If NASA did not procure the detectors for the mission, the Euclid project would do so.

## DAY 2—JANUARY 19, 2012

### WFIRST and Euclid and Their Impact on Dark Energy Research

*Speaker: Michael Turner, University of Chicago; expert in dark energy and U.S. science policy*

**Guiding Questions**

1. How do you see Euclid and WFIRST contributing to dark energy studies?
2. What do you see as the impact of U.S. participation in Euclid on U.S. dark energy efforts?

**Session Summary**

Reminding the committee that he is an advocate for dark energy and for U.S. astronomy, Michael Turner opened by remarking that the WFIRST mission is highly optimized to address science priorities of NWNH. In contrast, Euclid does not achieve as many of the science goals of WFIRST or the near-infrared survey science. He noted that the United States has the largest dark energy community, and yet only a small fraction of that group would benefit from Euclid. He said he believes a small investment in Euclid will have a negative impact on WFIRST and cautioned that small investments can grow larger than anticipated. To illustrate these two points he made comparisons to the recent WMAP/Planck experience. In comparing the potential impact of Euclid and WFIRST, Turner said that Euclid's lack of a supernovae survey capability is significant because that method is the only proven method of studying dark energy. He said, if weak lensing surveys do not realize the science results that are expected, then the figure of merit for WFIRST would be twice that of Euclid. Furthermore, BAO surveys are not proven to perform as well as the Fisher matrix estimates used to characterize their performance. He said the current WFIRST design is better than Euclid, and Euclid's design will involve under-sampled infrared pixels, have an undersized aperture, and have an inferior point spread function (because of the obstructed field of view). Turner concluded his presentation by reminding the committee that Europe has its own financial issues right now, and limiting the U.S. financial exposure to reduce risk of cost growth is important while still trying to ensure mission success for Euclid. One possible scenario is having two complementary satellites. During the discussion, Turner clarified that there are many issues that threaten WFIRST and, although WFIRST is not a dark energy mission alone, joining Euclid would dramatically increase the threat to WFIRST because a mis-perception exists that WFIRST is primarily a dark energy mission and because to non-experts the Euclid hardware appears superior to that of WFIRST.

## Discussion of Euclid and WFIRST Gravitational Lensing Capabilities

*Speaker: Chris Hirata, California Institute of Technology; expert in dark energy and gravitational lensing*

**Guiding Questions**

1. What is your assessment of Euclid's lensing capability?
2. How essential is ground-based data for Euclid lensing analysis?
3. What are the overlaps and synergies between Euclid and WFIRST planned lensing measurements?
4. What are the synergies between LSST and Euclid lensing analysis?

**Session Summary**

Chris Hirata started his presentation by noting what is needed by a weak lensing program for which obtaining statistics, shape measurement, and photometric redshifts are all goals, and he noted that there is no requirement to do all of these surveys from the same platform. He reviewed the imagining capabilities of LSST, WFIRST, and Euclid—noting that each has unique capabilities. He pointed out that LSST has six-band optical imaging and time domain capabilities; WFIRST is designed with deep, high-resolution NIR imaging (2 of the 3 bands are fully sampled); and Euclid will have high-resolution optical imaging. Hirata noted that among the advantages of LSST are that its many exposures will allow subsets of the data, it will cover the entire southern sky, it will provide a complete complement of optical filters, and it is the most advanced of the Stage IV projects. He said that the angular resolution of LSST, as well as the complications inherent in ground-based point spread function (PSF), are both disadvantages for

LSST. He said that Euclid will have the highest resolution of the three and will have large sky coverage, including lots of galaxies and will have a stable PSF with few dyanmic degrees of freedom (DOFs). The disadvantages of Euclid, he said, are that it will construct only one galaxy-shear map, and will have the charge transfer inefficiency issues that are common to space-based CCD detectors. Hirata noted that he does not see how the Euclid data sets could be divided into subsets, which would be a concern. For WFIRST, the advantages he noted were the inclusion of two high-resolution shape filters (the only project with high-resolution multicolor imaging, he noted); an unobstructed telescope; and, as with Euclid, WFIRST will have a stable PSF with few dynamic DOFs. The disadvantages of WFIRST were a small area, only 2,700 square degrees, in baseline mission, and he noted that the HgCdTe detectors have unique systematics. If the United States is part of Euclid, he said, then the United States might reallocate extragalactic survey time on WFIRST to deep mode survey to limit duplication. Hirata said that ground-based optical imaging will be required for both Euclid and WFIRST and that LSST depth will be more than sufficient for both Euclid and WFIRST. BAO on WFIRST will include "deep" surveys (parallel to NIR imaging survey) and "wide" surveys (BAO only) parts, and, Hirata noted, the BAO survey Euclid will provide is similar to the "wide" BAO on WFIRST, so it might make sense to perform WFIRST BAO surveys all in the deep mode. In concluding his presentation, Hirata reminded the committee that Stage IV weak lensing is going to be hard from the ground or from space. Euclid provides a unique high-resolution imaging capability over a wide field, and he would advocate for overlapping (or nested) footprints of the WFIRST and Euclid missions. He said that exploiting these scientific opportunities, including running analysis and cross correlating, will be much easier if the United States has people intimately familiar with both projects.

## Discussion of WFIRST and Euclid Exoplanet Microlensing

*Speaker: David Bennett, University of Notre Dame; expert in exoplanets and gravitational microlensing; member of the WFIRST Science Definition Team*

### Guiding Questions

1. What is your assessment of Euclid microlensing capabilities?
2. What are the likely microlensing capabilities of WFIRST? How will these evolve if the United States contributes infrared detectors to Euclid?
3. What are the synergies/overlaps between the two missions as currently conceived?
4. If U.S. scientists have access to Euclid data, what is most important for the exoplanet/microlensing community?

### Session Summary

David Bennett delivered a presentation entitled "Exoplanet Microlensing Surveys with WFIRST and Euclid." Bennett started with reviewing why space-based microlensing is important and what unique science a space-based microlensing survey could provide, including complements to Kepler surveys. He discussed space-based versus ground-based data sensitivity and remarked that some ground-based confusion can be resolved with space-based data. He briefly reviewed the science basis for measuring masses with regard to high magnification, lens systems, and microlensing parallax. In the second half of his presentation he responded to the questions asked in advance by the committee. He noted that the main drawback to Euclid is programmatic: the exoplanet program is not part of the core science program for Euclid. With regard to microlensing capabilities, Bennett reported that the photometric detection rate for the Euclid infrared channel and the WFIRST Interim Design Reference Mission are about the same and that the difference in photometry will be in the detection of inner planets (near the habitable zone) where

low-amplitude signals occur at low magnification—which will be easier with WFIRST. For lens identification and mass measurements, he said that relative astrometry will benefit more from the higher WFIRST angular resolution in the infrared. However, the high angular resolution Euclid optical data is probably better than the Euclid infrared data for these astrometric measurements. He also noted that no detailed mass measurement simulations have been done for either mission. The optimal microlensing fields, he reported, are highly obscured and four times more photons are detected in the infrared and that HgCdTe detectors are much better than CCDs in this regard, but a 2 square degrees CCD field of view could compensate for this. Bennett remarked that orbital microlensing parallax measurements will be difficult with 1-month observing windows on Euclid. He said that if Euclid and WFIRST fly at the same time, then simultaneous observations of microlensing events would yield some L2-L2 microlensing parallax measurements if they are out of phase by $\pi$ and this would be an interesting possibility. But the microlensing community cannot make realistic plans for this because it depends on the timing of missions run by different agencies. If available, Bennett stated that early microlensing data would provide a long-time baseline for relative proper motion measurements and, therefore, would help to improve mass measurements for a large fraction of all WFIRST and Euclid discoveries. Bennett concluded by remarking that if Euclid does not do a microlensing program, then Euclid data is of little interest to the U.S. microlensing community.

During the discussion, Bennett clarified that although a microlensing program will not be a priority on Euclid before the 6.3-year dark energy program is complete, it is possible to get a few months of microlensing done early on, in part because the limited number of cosmology fields that can be observed at the same time as the microlensing fields. However, such a program would not be comparable with WFIRST. He commented again that he felt the two 1-month windows planned for Euclid's mission are the biggest issue for microlensing but that the optical component from Euclid helps to compensate for Euclid's poor angular resolution in the infrared. When asked about a baseline comparison between WFIRST and Euclid of the relative number of planets that could be found, he responded that the baseline is pretty similar per unit observing time, although WFIRST has a particular advantage in finding planets in the most difficult region (closest to the habitable zone), and WFIRST would be better in determining masses. The Euclid mission is not guaranteed to do any microlensing. He also reminded the committee that the main goal of exoplanet science is cataloging planets, but a big goal within that is identifying planets in habitable zones around nearby stars and how they may be similar or different to Earth. When asked about the benefit of having early access to Euclid data, Bennett replied that it would be useful to have data earlier than the 14-month data policy, but that it also depends on how much microlensing they do. Processing the data quickly depends somewhat on hardware, and it is possible to do orbital microlensing parallax, but this might be easier to with a dedicated ground telescope. Finally, when asked about quantifying the statement that mass measurement would be better with WFIRST, Bennett replied that people are currently working on this, but the answer is not available yet.

## Impact of Current and Future Developments in Microlensing on Euclid and WFIRST

*Speaker: Dimitar Sasselov, Harvard University; expert in exoplanets and gravitational microlensing*

### Guiding Questions

1. Have the Kepler results changed the importance of the WFIRST microlensing program?
2. What are the likely ground-based developments that will compete/complement planned Euclid and WFIRST activities?

**Session Summary**

In response to the first question, Dimitar Sasselov answered, yes, Kepler results strengthen the case for a complementary survey. One reason why the case is strengthened is because the Kepler survey has already uncovered a very significant fraction of planets within an orbital radius of 2 to 3 astronomical units (AU) of their stars.

Sasselov presented one viewgraph to accompany his discussion depicting expected results for an extended Kepler mission currently under review. This extended mission, he remarked, would provide completeness beyond 1 AU for planets with a radius larger than Earth. He said that going forward much work will be focused on the characterization of small planets—such as looking for bio-signatures in atmospheres—and this will require going beyond Kepler and the extended mission, and he noted that most of the overlap will be for small-mass stars. He said that smaller rocky planets are crucial to our understanding of planet formation. Answering a second question, Sasselov said that in the next few years he expects a lot of ground-based technologies will be focused on characterization, particularly with improvement in radial velocity measurements and imaging. The Kepler survey does not determine the mass of free-floating planets, but the high frequency of planets being discovered by Kepler makes an even stronger case for a microlensing survey.

When asked why the exoplanet community was not very supportive of WFIRST microlensing, Sasselov reminded the committee that spectroscopy of planetary atmospheres turned out to be very successful and a lot of community effort was put into bringing this success down to the smaller planets as well. With the excitement around this area, the younger exoplanet community became more involved in spectroscopy and so they do not see direct benefits of WFIRST microlensing. He also noted that where the microlensing benefit will come, indirectly, from increasing the understanding of the physical properties characterization of the planets and formation scenarios. He closed by noting that the results of Kepler, and inability to match them to the models, are increasing interest in microlensing.

## Lessons Learned from Similar Past NASA-ESA Collaborations

*Speaker: George Helou, California Institute of Technology; Deputy Director of the Spitzer Science Center; Director of the NASA Herschel Science Center*

**Guiding Questions**

1. What are the successes and failures of previous missions where NASA astrophysics has contributed to an ESA mission (ISO, Herschel, Planck)?
2. What are your recommendations for the framework for U.S. role in Euclid?

**Session Summary**

George Helou presented some lessons learned from collaborations between NASA and ESA on the Infrared Space Observatory (ISO), Spitzer, Hershel, and Planck missions. He said that ISO began as an ESA-only mission, with some U.S. individual participation as co-investigators on instrument teams and on the ISO Science Team and several U.S. "scientific associates" also involved. He noted that a late agreement was made for guaranteed time and access to open time competitions in exchange for use of the Deep Space Network. He said that NASA competed its guaranteed time independently. The U.S. community participated in the competition for open time and was allocated approximately 30 percent of the open time, which resulted with the United States having responsibility for approximately 25 percent of the ISO time. Helou said there were data analysis issues because the United States did not become more

involved until later in the project, but in the end the United States had about 25 percent of the first authors on papers published.

With Spitzer, a NASA Great Observatory, Helou said that about 20 percent of the observing time was allocated to the European community through competition, but there was no ESA investment in Spitzer. For Hershel, Helou said that the NASA contributions were used primarily for enabling detectors and that was crucial to the mission. He said the U.S. Hershel Instrument Team members had access to guaranteed time, and in addition three U.S. scientists were independently selected from the Hershel Science Team in open competition, the net result being that U.S. scientists received nearly half of the open time and participated on another 35 percent of the open time. Planck has two U.S. members on the science team and about 80 U.S. scientists on their teams, all with full access to data and software. NASA will provide engineering support for delivered hardware and support for mission design and planning, around 20-25 percent of the data analysis on Planck, and there will be a U.S. version of the Planck archive. Looking at all of the activities, Helou said it is interesting to note that all the hardware contributions are through instrument-related activities, and none are to ESA directly.

In concluding his presentation Helou said that both NASA and ESA can fund, build, and operate major missions. Euclid will happen, but Euclid by itself will not kill WFIRST, nor would NASA buying into Euclid. He said that the unique capabilities of the United States are in leading-edge technologies and more especially in human and institutional resources, and the United States do not want to lose this edge. He said that critical mass of participation is also important to think about, and he believes a single U.S. scientist on the science team could be risky. Helou suggested as a framework that NASA should make sure that data are available, and he noted that the United States needs to get science data system participation. Finally, Helou also believes that along with hardware, the hardware characterization and data reduction pipelines should be included as U.S. deliverables, keeping that expertise alive in the United States and ensuring we have appropriate data access later. Helou also said that NASA would need to fund selected science team members to set up teams capable of exploiting data in a timely fashion and that NASA would need to establish a U.S. science center to support all Euclid users as it has done for missions in the past. He said that most of that cost happens after launch, and the cost would depend on what tasks the United States is contributing to Euclid. In the discussion that followed, Helou clarified that the science data center operation would be much smaller than what would be hosted in Europe, but that this is important to help enable scientists inside the team and outside the team to have good access to the data.

## Discussion with NASA

*Speaker: Paul Hertz, Acting Director of the Astrophysics Division within NASA's Science Mission Directorate*

### Guiding Questions

1. What is the cost of the U.S. hardware contribution to Euclid?
2. In Mellier's presentation, we heard that Euclid would be interested in NASA providing support for PanSTARRS or other ground-based efforts. Is this consistent with NASA's plans?
3. Does NASA view a 10percent lead authorship as a necessary return?
4. Would a possible role for the U.S. scientists be taking the lead in the Legacy science role of combining Euclid photometry with ground-based (primarily U.S.) photometry and providing this data to the public?

**Session Summary**

Paul Hertz reviewed the president's fiscal year (FY) 2012 budget request, and he presented a table from the president's FY2012 budget request of specific budget allocations for the NASA recommendations from NWNH, projected through FY2016. Hertz stated that the $20 million to $30 million for the NIR detectors would constitute (and be reallocated from) about 20 percent of the augmentation of funds planned for FY2013-FY2014 within the run out of the president's FY2012 budget request for allocation by the division for NWNH priorities in the same time frame. He concluded that the contribution would thus have a small, albeit non-negligible, impact on those programs. Hertz also stated that expenditure of these funds on Euclid hardware would not impact the launch schedule for WFIRST, since according to current NASA budget projections, significant expenditure on the WFIRST mission would only commence in the 2017-2018 time frame, when JWST construction spending rolls off. As part of its participation in Euclid, NASA would also support a science team at an annual level of $1.5 million to $3 million. He also noted that because the budget table he displayed to the committee was composed last year it included both the IXO and LISA missions; however, those projects were no longer being supported, and those budget lines would probably go to fund concepts being studied under current requests for information. Hertz also said that the WFIRST-development budget item was not included on the chart but is of the order of $4 million per year. Finally, he showed a slide with quickly assembled NASA-estimated costs for the specific possible Euclid-related contributions in which the committee expressed interest on the meeting's first day—including NIR detectors, $20 million to $30 million; NIR detectors and characterization, $40 million to $50 million; reaction wheels, approximately $10 million; filter wheel, $20 million to $25 million; and supporting a U.S. science team, between $15 million to $30 million. He reminded the committee that a Guest Observer program and a U.S. science center to support involvement in Euclid are not being discussed with ESA as part of the current discussions. In the discussion that followed, Hertz clarified that NASA and ESA have discussed NASA's providing either the detectors, the reaction wheels, or the filter wheels, but not multiple hardware contributions. He said that ESA would prefer that the United States contribute the NIR detectors, and NASA had specifically discussed with ESA a hardware contribution that is linked to the science. When asked, Hertz also noted that NASA has not been involved in discussions with the EC, nor with NSF or the DOE, on the need for cooperation with ground-based surveys such as LSST, Pan-STARRS, or the Dark Energy Survey.

## Final Discussion Summary

In the final discussions, Paul Hertz (NASA) reminded the committee that the 17 current U.S. scientists involved in the EC do not have the right to share data outside the EC, and that part of what NASA would get from becoming a partner in Euclid in the manner described at this meeting would be data access for the entire U.S. science community. Hertz said that while a NASA-selected Euclid science team would be relatively small, it would be openly competed through peer review so that any U.S. scientist would have a chance to be on the team. Hertz also said that NASA has not discussed putting a U.S. scientist on the ECB. A question arose about how the ECB is appointed and Jason Rhodes (JPL) explained to the committee that the EC is self-organizing and created the ECB.

The discussion transitioned back to the hardware contribution, and various attendees gave their opinions and impressions on the relative merits of each. As the open session came to a close, the discussion concluded with final remarks on the 10-percent science return for U.S. scientists, where Hertz said that the inclusion of that statement in the request from ESA was meant to clarify that NASA would have an appropriate role in the science, and he reminded the committee that the details of the science return will be discussed by the EST.

# D
# Glossary

**Astro2010:** The 2010 National Research Council astronomy and astrophysics decadal survey.

**Astronomy and Astrophysics Advisory Committee:** A federal advisory committee chartered under the Federal Advisory Committee Act, the committee advises the National Science Foundation, the National Aeronautics and Space Administration, and the U.S. Department of Energy on selected issues within the fields of astronomy and astrophysics that are of mutual interest and concern to the agencies.

**AXAF:** See **Chandra.**

**Baryon acoustic oscillation (BAO):** Sound waves in the early universe generate fluctuations both in the cosmic microwave background spectrum and the matter (baryon) fluctuation spectrum.

**Chandra:** The Chandra X-ray Observatory, launched in 1999, one of NASA's four Great Observatories.

**Dark energy:** Hypothetical form of energy that causes the present-day expansion of the universe to accelerate.

**Dark Energy Survey (DES):** A ground-based survey to study the nature of dark energy by observing the distributions of galaxies and clusters of galaxies, weak gravitational lensing, and supernovae.

**Deep Space Network (DSN):** NASA's worldwide antenna network to support the exploration of the solar system.

**Epoch of Reionization:** The period during which the baryonic content of the universe is gradually ionized. The onset of reionization coincides with the emergence of the first ionizing (luminous) sources, at the end of the dark ages, and ends when the intergalactic medium is fully ionized.

**Euclid:** An medium-class mission selected by the European Space Agency for an upcoming launch to study dark energy.

**European Space Agency (ESA):** International organization of European states cooperating in space research and technology.

**Exoplanet:** An extrasolar planet, i.e., a planet orbiting a star other than the Sun.

**Filter wheel:** instrument component that contains filters to isolate particular wavelength regions.

**Galaxy cluster:** A large group of galaxies bound together gravitationally.

**Gravitational lensing:** Deflection of light by the gravitational potential associated with astronomical objects, such as stars, galaxies, and groups and clusters of galaxies. Two distinct regimes are important: (1) strong gravitational lensing, where the gravitational potential is deep enough to produce multiple images of a background source, and (2) weak gravitational lensing, where the gravitational potential distorts the appearance of background sources but does not create multiple images.

**Gravitational microlensing:** An intensification of light from a background star produced by the gravity of a mass, such as another star or an exoplanet that is aligned almost exactly along the line of sight.

**Hubble Space Telescope (HST):** Orbiting optical/ultraviolet/near-infrared space telescope launched in 1990 and refurbished at periodic intervals. Current Hubble Space Telescope cameras can image with ~0.1-arcsecond resolution and take ultraviolet spectra between 1100 and 3000 angstroms.

**Hyper Subprime Cam:** A camera on Japan's Subaru optical-infrared telescope, located at the summit of Mauna Kea on the island of Hawaii.

**Infrared:** Light with wavelength longer than visible light but shorter than radio waves. Near-infrared refers to the wavelength range from ~1 to 5 microns, mid-infrared is ~5 to 20 microns, and far-infrared extends from ~20 microns to ~200 microns, where the submillimeter begins.

**James Webb Space Telescope (JWST):** An infrared space observatory under construction, scheduled for launch in 2018 or later, which is the successor to the Hubble Space Telescope.

**Kepler:** A NASA satellite mission with a photometric monitor of 150,000 stars looking for transits of extra-solar planets ranging in size from Jupiter down to sub-Neptune and Earth-like in radius.

**KIlo-Degree Survey (KIDS):** A 1,500-square-degree public imaging survey with patches in both the Northern and Southern skies. The survey will use the OmegaCAM instrument mounted on the Very Large Telescope Survey Telescope.

**Large Synoptic Survey Telescope (LSST):** A priority of the *New Worlds, New Horizons* (Astro2010) decadal survey, LSST is large aperture, wide field survey telescope and 3,200 megapixel camera to image faint astronomical objects across the sky.

**Medium-class (M-class):** Medium-scale European Space Agency mission.

**Microlensing:** See **gravitational microlensing**.

**Near-infrared (NIR):** Wavelengths from ~1 to 5 microns. (Also see **infrared**).

**New Worlds, New Horizons (NWNH):** The 2010 National Research Council astronomy and astrophysics decadal survey report, *New Worlds, New Horizons in Astronomy and Astrophysics* (The National Academies Press, Washington, D.C.).

**Optical:** Wavelength range of light to which the human eye is sensitive, namely, 3,500 to 8,000 Å.

**Pan-STARRS-1:** Panoramic Survey Telescope and Rapid Response System, a wide-field (1.8 meter) imaging facility being developed at the University of Hawaii's Institute for Astronomy.

**Planck:** A European Space Agency satellite launched in 2009 to map tiny fluctuations in the cosmic microwave background radiation.

**Point spread function (PSF):** The point spread function describes the angular response of a telescope to a point-like source of light. Because of atmospheric turbulence and the finite resolving power of a telescope, light from point-like object is spread out in angle.

**Reaction wheels:** Wheels that provide enhanced guiding and stabilization of a spacecraft.

**Redshift:** The increase in wavelength of electromagnetic radiation (Doppler shift) caused by the motion of an object as described by the theory of special relativity, or by luminous material in a gravitational field as described by the general theory of relativity. In cosmology, it refers to the fractional increase in the wavelength of a photon received from a distant object, due to the expansion of the universe between emission and reception. Coupled with a cosmological model, redshifts can be used to determine the distance and look-back time of phenomena in the universe.

**Reionization:** See **Epoch of reionization**.

**Science Definition Team (SDT):** Team to help characterize a mission, in this case the WFIRST SDT.

**Sloan Digitized Sky Survey (SDSS):** Dedicated 2.5-meter ground-based telescope supporting repeated multicolor images of a quarter of the sky.

**Space Infrared Telescope Facility (SIRTF):** See **Spitzer Space Telescope.**

**Spitzer Space Telescope:** NASA's Space Infrared Telescope Facility, launched in 2003.

**Star cluster:** A group of stars formed at about the same time.

**Very Large Telescope (VLT):** Four 8-meter telescopes of the European Space Observatories, located in Chile.

**Weak lensing:** Fluctuations in the large-scale distribution of matter produce variations in the "shape" of space that alter the path that light takes from a distant galaxy to our telescopes. This gravitational lensing changes the shape of a galaxy and makes it appear more elliptical. By measuring the shapes of large numbers of galaxies, astronomers can detect this "weak lensing" effect and infer the large-scale distribution of matter.

**WFIRST:** Wide Field Infrared Survey Telescope, the top-ranked large space mission of **NWNH**.

**William Herschel Space Observatory:** A European Space Agency satellite launched in 2009 to study the formation of stars and galaxies at far-infrared and submillimeter wavelengths.

**XMM-Newton:** The European Space Agency's X-ray Multi-Mirror mission, named after Sir Isaac Newton, is an orbiting X-ray observatory launched in 1999. It features a large collecting area for X-ray spectroscopy.

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# Committee and Staff Biographical Information

DAVID N. SPERGEL (NAS) is the Charles A. Young Professor of Astronomy on the Class of 1897 Foundation and chair of the Department of Astrophysical Sciences at Princeton University. He was the W.M. Keck Distinguished Visiting Professor of Astrophysics at the Institute for Advanced Study. Dr. Spergel has made major contributions to cosmology, astroparticle physics, galactic structure, and instrumentation. He led the theoretical analysis for the Wilkinson Microwave Anisotropy Probe (WMAP), invented novel coronagraphs for planet detection, originated and explored the concept of self-interacting dark matter, and showed that the Milky Way is a barred galaxy. He was an Alfred P. Sloan Research Fellow and received the following awards: NSF Presidential Young Investigator Award, the Helen B. Warner Prize, the Bart Bok Prize, the AAS Second Century Lecturer, a MacArthur Fellowship and the R.R. Shaw Prize in Cosmology. He is a member of the Science Working Group for the Wilkinson Microwave Anisotropy Probe (WMAP). He is a member of the American Astronomical Society (AAS), the American Physical Society (APS), and the International Astronomical Union (IAU). Dr. Spergel served on the National Science Foundation's (NSF's) Advisory Committee for Astronomical Sciences, the Theory, Experimental and Laboratory Astrophysics Subcommittee and the Scientific Advisory Board for the Hayden Planetarium. He is the editor of the Princeton Series in Astrophysics and the Science Advisor for NPR's "Earth & Sky" radio program. He received an A.B. (astronomy summa cum laude, Phi Beta Kappa) from Princeton University; he was Harvard Travelling Scholar at Oxford University; and he received an A.M. in astronomy and a Ph.D. in astronomy from Harvard University. His NRC service includes current membership on the Space Studies Board. Previously, he has served as chair on the Astro2010 Panel on Cosmology and Fundamental Physics and as a member on the Committee to Review the Science Requirements for the Atacama Large Millimeter Array (ALMA), the Committee on Physics of the Universe, the Committee on Astronomy and Astrophysics, the Committee on Gravitational Physics, the Organizing Committee for the Eighth and Ninth Annual Symposiums on Frontiers of Science, the Task Group on Space Astronomy and Astrophysics, and the Panel on Cooperation with the USSR in High Energy Astrophysics.

CHARLES ALCOCK (NAS) is the director at the Harvard-Smithsonian Center for Astrophysics and a professor of astronomy at Harvard University. Prior to his position at Harvard, Dr. Alcock was at Lawrence Livermore National Laboratory for 15 years and afterward as a professor at the University of Pennsylvania. Dr. Alcock was the principal investigator (PI) of the Taiwanese-American Occultation Survey, an international project involving scientists from eight institutions in the United States, Taiwan, and South Korea. He was also the PI on the W. M. Keck Cyber Universe Survey Project at the University of Pennsylvania, which develops high-speed, automated data analysis pipelines for small survey projects, and he was the PI of the MACHO Project, an international project involving scientists from seven institutions in the United States, Australia, Canada, and Britain. His research interests include studying massive compact halo objects, comets, and asteroids; the outer solar system; cosmic dark matter; large astronomical surveys; astronomical data mining; and virtual observatory technologies. Dr. Alcock was a chair of the Observatories Council of the National Optical Astronomy Observatories and is an ex officio

member of the board of AURA. He received his Ph.D. in astronomy from the California Institute of Technology (Caltech). Dr. Alcock's previous NRC membership includes the Committee on Astronomy and Astrophysics, the Panel to Review Terrestrial Planet Finder Science Goals, and the Panel on Theory and Computation in Astronomy and Astrophysics.

RACHEL BEAN is an associate professor in the Department of Astronomy at Cornell University. Her earlier work focuses on cosmological theories and how they can be constrained using observations such as the cosmic microwave background (CMB) and large scale structure data (galaxies and clusters of galaxies). Her current research includes work to establish the nature of dark energy and dark matter and how observations can be used to distinguish between competing theories. She is also interested in the application of high-energy particle theory to understanding how initial conditions for seeding structure were established in the early universe. She is a member of the WFIRST Science Definition Team. She received the Affinito-Stewart Award from the President's Council of Cornell Women, the NASA Group Achievement Award for WMAP, and the Cottrell Scholar Award from the Research Corporation. Most recently, Dr. Bean is a recipient of the 2010 Presidential Early Career Awards for Scientists and Engineers through the NSF. She earned her Ph.D. in physics from Imperial College, University of London. Dr. Bean previously served as a member on the NRC Astro2010 Panel on Cosmology and Fundamental Physics.

CHARLES L. BENNETT (NAS) is the Alumni Centennial Professor of physics and astronomy and Gilman Scholar at Johns Hopkins University. Dr. Bennett's research interests include experimental cosmology and astrophysical instrumentation. He was the PI for the WMAP mission, which quantitatively specified the age, content, history, and other key properties of the universe with unprecedented precision. Previous to his work on WMAP, Dr. Bennett was the deputy PI of the Cosmic Background Explorer (COBE) Differential Microwave Radiometers instrument. He is also the PI for the Cosmology Large Angular Scale Surveyor (CLASS) ground-based experiment. Dr. Bennett received the Shaw Prize, the Comstock Prize in Physics, the Harvey Prize, the Henry Draper Medal, and he shared the Gruber Prize in Cosmology. From 1984 to 2005, Dr. Bennett was an astrophysicist at the NASA Goddard Space Flight Center, where he won the NASA Outstanding Leadership Medal and twice won the NASA Exceptional Scientific Achievement Medal. Dr. Bennett is a member of the American Academy of Arts and Sciences and a fellow of the American Association for the Advancement of Science (AAAS) and APS. Dr. Bennett received his Ph.D. in physics from the Massachusetts Institute of Technology. Dr. Bennett's previous NRC service includes the Committee on Astronomy and Astrophysics, the Space Studies Board, the NASA Astrophysics Performance Assessment (NAPA) Committee, and the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions.

ROMEEL DAVÉ is an assistant professor of astronomy at the University of Arizona. His work centers on using cosmological hydrodynamic simulations to understand galaxy formation and intergalactic medium evolution within a hierarchical structure formation context, focusing on constraining models through detailed comparisons versus multiwavelength observations. After completing his doctorate, Dr. Davé became a Lyman J. Spitzer Fellow at Princeton University and then he was a Hubble Fellow at the University of Arizona. He joined the faculty at the University of Arizona in 2003. He has a broad range of additional research interests, including constraining cosmological parameters, the epoch of reionization, the nature of dark matter, the stellar initial mass function, and numerical hydrodynamics. He is on the board of the Arizona Theoretical Astrophysics Program and the Arizona High Performance Computing Committee and has served on various ground- and space-based telescope time-allocation committees. Dr. Davé received his Ph.D. in astronomy from University of California, Santa Cruz. He previously served as a member on the NRC's Astro2010 Panel on Galaxies Across Cosmic Time.

ALAN DRESSLER (NAS) is an observational astronomer at the Observatories of the Carnegie Institution. His principal areas of research cover the formation and evolution of galaxies and the study of

star populations of distant galaxies. Dr. Dressler has made significant contributions in the understanding of galaxy formation and evolution, including effects of the environment on galaxy morphology. He was a leader in the identification of the "great attractor," which causes a large distortion of the Hubble expansion. From 1993-1995 Dr. Dressler chaired the Associated Universities for Research in Astronomy (AURA) committee "HST & Beyond: Exploration and the Search for Origins" that presented NASA with A Vision for Ultraviolet-Optical-Infrared Space Astronomy, which now form a substantial component of the NASA program in astrophysics. Dr. Dressler received his Ph.D. in astronomy from the University of California. He is currently a member of the NRC's Space Studies Board. Previously, he chaired the Astro2010 Panel on Electromagnetic Observations from Space and the Panel on Optical and Infrared Astronomy from the Ground of the 2000 Astronomy and Astrophysics Survey Committee, and served as a member on the Committee on Setting Priorities for NSF-Sponsored Large Research Facility Projects.

DEBRA M. ELMEGREEN is the Maria Mitchell Professor of Astronomy in the Department of Physics and Astronomy at Vassar College. Her research interests include structure, interactions, and star formation in galaxies in the local universe and at high redshift. Dr. Elmegreen observes in optical, near-infrared, and radio wavelengths. Her research often involves undergraduates, through the Undergraduate Research Summer Institute and the Keck Northeast Astronomy Consortium. She is a member and president of AAS and has served on several AAS committees, including the Astronomy Education Board as council liaison, as AAS representative to USNC-IAU board, and on the Warner and Pierce Prize Committee as a member and a chair. She served on NSF's External Review Committee for the CTIO Small and Moderate Aperture Research Telescope System, the Program Review Panel for the National Optical Astronomy Observatory, and the Waterman Prize Committee; HST's Telescope Allocation Committee and Space Telescope Users Committee (member and chair); Spitzer Space Telescope's Allocation Committee and the Postdoctoral Fellowship Committee (member and chair); NOAO's Systems Committee on Optical/Infrared Astronomy and the Survey Telescope Allocation Committee; National Radio Astronomy Observatory's Users Committee and the Telescope Allocation Committee. She has also served on several scientific organizing committees. Dr. Elmegreen received her Ph.D. in astronomy from Harvard University. Her current membership includes the Board on Physics and Astronomy, the Astronomy and Astrophysics Advisory Committee, and as an ex officio member on the U.S. National Committee for the International Astronomical Union. She is a Fellow of the American Association for the Advancement of Science. She previously served as a member on the NRC Committee on Decadal Survey on Astronomy and Astrophysics 2010 and the Panel on Implementing Recommendations from New Worlds New Horizons Decadal Survey.

JOSHUA A. FRIEMAN is a scientist at the Theoretical Astrophysics Group at the Fermi National Accelerator Laboratory (Fermilab), which he headed from 1994 to 1999, and is a professor of astronomy and astrophysics at the University of Chicago, where he is also a member of the Kavli Institute for Cosmological Physics. He is a fellow of APS and AAAS and a trustee of the Aspen Center for Physics. He served on the Executive Committee of the APS Division of Astrophysics. Dr. Frieman's research centers on theoretical and observational cosmology, including studies of the nature of dark energy, the very early universe, gravitational lensing, the large-scale structure of the universe, and supernovae as cosmological distance indicators. He is the author of more than 200 publications, has led the Sloan Digital Sky Survey (SDSS) Supernova Survey, and served as chair of the SDSS Collaboration Council. He is a founder of the Dark Energy Survey and serves as co-chair of its Science Committee. He earned a B.Sc. degree from Stanford University and a Ph.D. in physics from the University of Chicago. Dr. Frieman's previous NRC membership includes service the Committee on Decadal Survey on Astronomy and Astrophysics 2010 and the Panel on Particle, Nuclear, and Gravitational-Wave Astrophysics.

THOMAS A. PRINCE is a professor of physics at the Caltech and director of the W.M. Keck Institute for Space Studies. He is also a senior research scientist at the Jet Propulsion Laboratory (JPL). Previously, Dr. Prince served the chief scientist at JPL. He began his research career in experimental cosmic ray

astrophysics before coming to the Caltech campus to work in the area of experimental gamma-ray astronomy, collaborating with the high-energy astrophysics group at JPL. His current research uses the Palomar Transient Factory for large area sky surveys of compact objects. Dr. Prince was the U.S. Mission Scientist for the Laser Interferometer Space Antenna (LISA) and formerly a member of the ground-based Laser Interferometer Gravitational-wave Observatory (LIGO). He is a fellow of APS. Dr. Prince received the NASA Distinguished Service Medal. He received his Ph.D. in physics from the University of Chicago. Dr. Prince previous NRC service includes co-chair of the Committee on Astronomy and Astrophysics and membership on the Panel on Theory and Computation in Astronomy and Astrophysics and the Space Studies Board.

MARCIA J. RIEKE is a Regents' Professor of Astronomy and an astronomer in the Department of Astronomy at the University of Arizona. Her research interests include infrared observations of galactic nuclei and high-redshift galaxies. She has served as the deputy PI on the near-infrared camera and multiobject spectrometer for HST (NICMOS), and she is currently the PI for the near-infrared camera (NIRCam) for the James Webb Space Telescope. Dr. Rieke has worked on the Spitzer Space Telescope as a co-investigator for the multiband imaging photometer, as outreach coordinator, and as a member of the Science Working Group. She was also involved with several infrared ground observatories, including the Multiple Mirror Telescope in Arizona. Dr. Rieke is a fellow of the American Academy of Arts and Sciences. She received her Ph.D. in physics from Massachusetts Institute of Technology. She currently serves on the NRC's Space Studies Board. Her previous service includes as co-vice chair of the Committee on Decadal Survey on Astronomy and Astrophysics, as a member on the Astronomy and Astrophysics Survey Committee, as a vice chair on the Panel on Ultraviolet, Optical, and Infrared Astronomy from Space, and as a member on the Steering Committee for the Task Group on Space Astronomy and Astrophysics and the U.S. National Committee for the International Astronomical Union.

***Staff***

DAVID LANG, *Co-Study Director,* is a program officer for the NRC's Board on Physics and Astronomy (BPA) and joined the NRC in 2004. Mr. Lang received a B.S. in astronomy and astrophysics from University of Michigan and a master's degree in engineering and public policy from University of Maryland. At BPA he has operated several large committees on scientific and technical policy issues including spectrum management and telecommunications, astronomy and astrophysics, particle physics, plasma physics, and materials science. He is also responsible for developing future studies for the board through the identification of pressing policy issues and discussions with federal agency sponsors and the science community.

CARYN JOY KNUTSEN, *Co-Study Director,* is currently an associate program officer with the NRC's Board on Physics and Astronomy. She came to the BPA in 2006 as a senior program assistant after completing a B.S. in mathematics from the University of Colorado at Colorado Springs in 2006. While attending the University of Colorado at Colorado Springs she also earned two certificates in industrial mathematics. At the BPA, she has been involved, through various roles, in multiple committees covering topics included physics education, astronomy and astrophysics, nuclear physics, plasma physics, and materials science. In 2010 she received an NAS Distinguished Individual Service Award.

LEWIS B. GROSWALD, research associate, joined the Space Studies Board (SSB) as the Autumn 2008 Lloyd V. Berkner Space Policy Intern. Mr. Groswald is a graduate of George Washington University, where he received a master's degree in international science and technology policy and a bachelor's degree in international affairs, with a double concentration in conflict and security and Europe and Eurasia. Following his work with the National Space Society during his senior year as an undergraduate,

Mr. Groswald decided to pursue a career in space policy, with a focus on educating the public on space issues and formulating policy.

AMANDA R.THIBAULT, research associate, joined the Aeronautics and Space Engineering Board in 2011. Ms. Thibault is a graduate of Creighton University where she earned her B.S. in atmospheric science in 2008. From there she went on to Texas Tech University where she studied lightning trends in tornadic and non-tornadic supercell thunderstorms and worked as a teaching and research assistant. She participated in the VORTEX 2 field project from 2009-2010 and graduated with a M.S. in atmospheric science from Texas Tech in August 2010. She is a member of the American Meteorological Society.

CATHERINE A. GRUBER, editor, joined the Space Studies Board 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 also worked as an outreach assistant for the 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.

DIONNA WILLIAMS is a program associate with the SSB, having previously worked for the National Academies' Division of Behavioral and Social Sciences and Education for 5 years. Ms. Williams has a long career in office administration, having worked as a supervisor in a number of capacities and fields. Ms. Williams attended the University of Colorado, Colorado Springs, and majored in psychology.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, BPA, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

DONALD C. SHAPERO, director, Board on Physics and Astronomy, received a B.S. 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., Dr. Shapero 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 National Research Council 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 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 Astronomical Society and the International Astronomical Union and a fellow of both the APS and the AAAS. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.