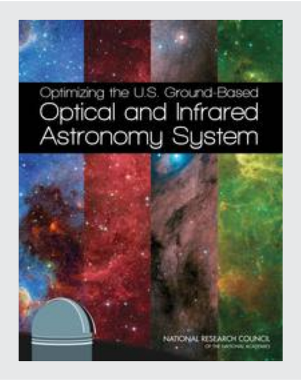

Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System (2015)

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Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System

Committee on a Strategy to Optimize the U.S. Optical and Infrared System
in the Era of the Large Synoptic Survey Telescope (LSST)

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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COMMITTEE ON A STRATEGY TO OPTIMIZE THE U.S. OPTICAL AND INFRARED SYSTEM IN THE ERA OF THE LARGE SYNOPTIC SURVEY TELESCOPE (LSST)

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Preface

Ground-based optical and infrared astronomy in the United States has a long record of world-leading achievement. In the late 1950s and early 1960s, Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO), both now part of the National Optical Astronomical Observatory (NOAO), were formed to build and operate telescopes that would provide public access to world-class facilities. These complemented the private telescopes of a handful of universities and research institutes, such as the 200-inch Hale telescope at Palomar Observatory, dedicated in 1948. In recent decades, new and more powerful public and private telescopes and instruments have been built. As these facilities have become larger and more sophisticated, they have become more expensive to build and operate, and this trend is expected to continue. These developments have led to partnerships among and between public, private, and international parties. The initial concept for an integrated U.S. Optical and Infrared (OIR) System to enable public access to public and private telescopes and instruments stems from the 1995 National Research Council (NRC) report *A Strategy for Ground-Based Optical and Infrared Astronomy*[1] (hereafter the McCray report). That report stressed the need for an efficient infrastructure for OIR astronomy with a range of apertures and capabilities. The first use of the term "OIR System" dates to the 2001 NRC decadal

NOTE: Acronyms, especially those denoting individual instruments and missions, are defined in Appendix C.

[1] National Research Council (NRC), 1995, *A Strategy for Ground-Based Optical and Infrared Astronomy*, National Academy Press, Washington, D.C.

survey, *Astronomy and Astrophysics in the New Millennium*[2] (AANM). Today's expanded vision of a U.S. OIR System also includes public access to data archives, especially from large surveys. In AANM and throughout this report, the term "OIR System" refers to *ground-based* optical and infrared astronomical facilities and resources.

Federal investment in astronomy is driven by the science priorities established in the consensus reports of the NRC decadal surveys. The astronomy and astrophysics decadal surveys are forward-looking reports that focus on proposing new facilities to realize the priorities they establish. They do not consider the relative merits of the proposed facilities versus the existing or under-construction facilities. To address this aspect, the AANM decadal survey report led to a 2006 Senior Review Committee to balance support for the current activities of the National Science Foundation (NSF) against the desire to fund new ones. Similarly, the 2010 *New Worlds, New Horizons in Astronomy and Astrophysics*[3] (NWNH) decadal survey report recommended that the NSF Division of Astronomical Sciences (AST) hold an internal review to determine which facilities might be divested in order to enable support for new facilities and science analysis. Subsequently, NSF AST formed the Portfolio Review Committee (PRC) to make recommendations considering its grants program, its current and future telescope suite, and any potential for divestment. Its 2012 report is *Advancing Astronomy in the Coming Decade: Opportunities and Challenges.*[4]

In its 2013 annual report,[5] the Astronomy and Astrophysics Advisory Committee (AAAC) recommended that NSF AST request "a report led by the NRC's Committee on Astronomy and Astrophysics (CAA) to help define a revised national OIR system, with a focus on the required instruments, telescopes, and public access to enable both the best science and broadest community participation in the LSST [Large Synoptic Survey Telescope] era."[6] The details of such a study were discussed within the CAA, which is a joint standing committee of the NRC Board on Physics and Astronomy (BPA) and the Space Studies Board (SSB). NSF AST subsequently sponsored the current study through the BPA and

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[2] NRC, 2000, *Astronomy and Astrophysics in the New Millennium*, The National Academies Press, Washington, D.C.

[3] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[4] National Science Foundation (NSF), 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

[5] NSF, 2013, *Report of the Astronomy and Astrophysics Advisory Committee,* http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2013_130308finalreport.pdf.

[6] NSF, 2013, *Report of the Astronomy and Astrophysics Advisory Committee*, p. 13.

SSB to make strategic recommendations for optimizing nighttime (non-solar) ground-based optical and infrared astronomy, considering the PRC recommendations and the decadal report priorities. Discussions between NSF, NRC, and CAA led to the following charge:

Statement of Task

In order to position the observational, instrumentation, data management, and support capabilities of the U.S. optical and infrared (O/IR) astronomy system to best address the science objectives identified in the 2010 report entitled *New Worlds, New Horizons in Astronomy and Astrophysics* and *Vision and Voyages for Planetary Science in the Decade 2013-2022* and to help achieve the best science return from the National Science Foundation investment in O/IR astronomy over the next 10-15 years, the National Research Council will convene a committee to write a short report that will recommend and prioritize adjustments to the U.S. ground-based O/IR system that will better position the system to address the *New Worlds, New Horizons* science objectives over the next 10-15 years. The committee will consider needs and strategies for several interrelated components of the system: existing and planned focal plane instrumentation; focal plane instrumentation and technology development; and data management, processing, mining, and archiving. The committee may make recommendations or offer comments on organizational structure, program balance, and funding, with discussion of the evidentiary bases, as appropriate.

The Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope[7] was formulated to include a range of expertise and geographic and institutional diversity. The committee met three times in person: at the Keck Center of the National Academies in Washington, D.C., on July 31-August 1 and December 2-3, 2014, and at the Arnold and Mabel Beckman Center in Irvine, California, on October 12-13, 2014. Approximately 20 conference calls were held between July 2014 and January 2015. Since community input was an important component of the study, short white papers[8] were solicited to respond to any topic related to the charge of optimizing the U.S. OIR System for the best science return or to answer any of 10 general questions. The committee received 39 white papers from a total of 318 coauthors, plus 4 general comments. The responses primarily addressed LSST follow-up; the OIR System; instrumentation, including software; and data. There were also collective comments from 22 instrumentalists on topics related to instrumentation. At the committee's in-person meetings, there were presentations by and discussions with NSF, OSTP, NASA, ESO, NRAO, AURA, observatory directors, data and archive specialists, and adaptive optics specialists during sessions open to the public. The current study draws from the scientific priorities and the conclusions and recommendations of both NWNH and the 2011

[7] The name of the committee reflects the name of the study as proposed to NSF and agreed upon by NSF, NRC, and CAA.

[8] The solicitation letter is shown in Appendix A, along with titles and authors of the white papers.

NRC planetary science decadal survey *Vision and Voyages for Planetary Science in the Decade 2013-2022*[9] (VVPS) as well as the NSF PRC report,[10] along with information contained in the McCray report,[11] the NOAO System Roadmap,[12] the *LSST Science Book*,[13] and similar reports. Solar and space physics optimization strategies are beyond the purview of this committee and were not addressed in this report.

NWNH had extensive coverage of OIR science and instrumentation, whereas the VVPS focus was primarily on space-based missions. VVPS highlighted LSST as important for solar system studies of near-Earth objects, Kuiper Belt objects, and comets, and noted that NASA access to the Infrared Telescope Facility (IRTF) and W.M. Keck Observatory as well as access to Keck, Magellan, and MMT (formerly the Multiple Mirror Telescope) through the Telescope System Instrumentation Program (TSIP), enabled critical observations for planetary studies, partly to support space-based planetary missions. VVPS supported the recommendations and priorities of NWNH regarding LSST and future giant telescopes.

Through discussions with NSF AST officers, the committee interpreted the charge in the context of the statement of task as well as the report title that was given in the NSF project prospectus. Thus, LSST was taken to be one of the central components of the study, and the report was to include all other elements of ground-based OIR astronomy in the United States as well. The "LSST era" was interpreted to emphasize the democratization of cutting-edge astronomy that will be enabled through massive surveys made available in an accessible format to the entire U.S. professional astronomical community, as well as the collaborative and synergistic efforts needed with giant (TMT, GMT) telescopes and with the rest of the OIR System. The committee was also explicitly asked by NSF to consider whether the Southern Astrophysical Research (SOAR) telescope might have a future role for follow-up observations. The committee limited the inventory of U.S. OIR facilities to telescopes with apertures 2 meters or larger in order to be complete at this level, although in several places the importance of telescopes smaller than this is noted. NSF asked the committee to consider any science advantages in coordinating federal telescopes but instructed that such coordination should not involve a discussion of the current management or possible efficiencies through merged management. For all topics, the discussion was to be centered on science drivers.

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[9] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C.

[10] NSF, 2012, *Advancing Astronomy in the Coming Decade.*

[11] NRC, 1995, *A Strategy for Ground-Based Optical and Infrared Astronomy*.

[12] National Optical Astronomy Observatory, 2012, Ground-based O/IR System Roadmap Committee Community Survey Summary of Results from U.S. Based/Sponsored Respondents, http://ast.noao.edu/sites/default/files/SummaryDocumentSystemRoadmapCommunitySurveyV1.5.pdf.

[13] Large Synoptic Survey Telescope, 2009, *Large Synoptic Survey Telescope Science Book Version 2.0*, November, http://www.lsst.org/lsst/science/scibook.

The guidelines given by NSF regarding funding were that the current era is one of essentially flat budgets and that the committee was not to work with a budget (although comments on the new Mid-Scale Innovations Program (MSIP) were invited). Therefore, detailed cost estimates are not part of this report, and methods to provide funding for specific recommendations are not given. However, the committee was cognizant of the fact that very costly recommendations would not be actionable, and an approximate total figure for the recommendations is given in the Epilogue. Program balance was interpreted in the context of maintaining instrumentation and technology development, small through large facilities, and expertise needed to accomplish the decadal science objectives. The committee was explicitly instructed by NSF not to discuss the astronomy and astrophysics grants program. Space-based missions and non-OIR ground-based facilities are discussed in the report in the context of synergies with ground-based OIR observations, but optimization is considered only for the OIR operations, as per the charge to the committee.

The committee followed NRC style such that conclusions should be at a high level rather than summarizing every section and that recommendations should be restricted to a few high-level items. The committee conclusions are based on material cited in the report, and the recommendations are directed toward NSF as the study sponsor.

It is a pleasure to acknowledge the many individuals and organizations that have assisted in producing this report. We thank James Ulvestad, Vernon Pankonin, and Patricia Knezek from NSF AST for inviting and sponsoring this study and for their helpful overview of the AST Division and discussions related to the statement of task. We appreciate the observatory directors, agency representatives, and other astronomers who, at our request, made formal presentations at in-person meetings in Washington, D.C., and in Irvine, California, to help inform the committee's deliberations,[14] and thank the observatory personnel who supplied the requested demographic information (Appendix B) and technical information (Table 3.2) listed in this report. We are grateful to the community for input in the form of white papers, comments, and helpful answers to questions we posed. We acknowledge the careful work of the reviewers, the Report Monitor Robert Sproull and the Report Coordinator Martha Haynes, in helping to improve the report. Finally, we recognize and applaud the support and dedication of NRC staff, including program officer David Lang, who was our study director, James Lancaster, director of the Board on Physics and Astronomy, Michael Moloney, director of the Space Studies Board, program coordinator Linda Walker, research associate Katie Daud, reports officer

[14] Meeting agendas, speakers, and presentations are at the National Academies website at http://sites.nationalacademies.org/BPA/BPA_087934.

Elizabeth Panos, and the Report Review Committee staff Janice Mehler. I am very grateful to my colleagues on this committee (listed on p. v of this report), who served with wisdom, diligence, and good humor.

Debra Meloy Elmegreen, *Chair*
Committee on a Strategy to Optimize the
U.S. Optical and Infrared System in the Era of the
Large Synoptic Survey Telescope (LSST)

Acknowledgment of Reviewers

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

Roger Blandford, Stanford University,
Daniel Eisenstein, Harvard-Smithsonian Center for Astrophysics,
Sandra Faber, University of California, Santa Cruz,
Eileen Friel, Indiana University,
Günther Hasinger, University of Hawaii,
Suzanne Hawley, University of Washington,
George Helou, California Institute of Technology,
William Herbst, Wesleyan University,
George Rieke, University of Arizona,
Beth Willman, Haverford College, and
Charles Woodward, University of Minnesota.

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 Robert F. Sproull, Oracle, and Martha P. Haynes, Cornell University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

Revolutionary discoveries undoubtedly will follow from the realization of the Large Synoptic Survey Telescope (LSST) under construction, the planned 30-meter-class telescopes, and new instrumentation on existing optical and infrared (OIR) telescopes. The challenge is to extract the best science from these and other astronomical facilities in an era of potentially flat federal budgets for both the facilities and the research grants necessary to exploit them. In the 2010s, there is increasing scientific opportunity combined with decreasing purchasing power. This report describes a vision for a nighttime U.S. OIR System that includes a telescope time exchange designed to enhance science return by broadening access to capabilities for a diverse community; an ongoing planning process to identify and construct next-generation capabilities to realize decadal science priorities; and near-term critical coordination, planning, training, and instrumentation needed to usher in the era of LSST and giant telescopes.

The guiding principles used by the National Research Council's (NRC's) Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (LSST) in its deliberations were as follows:

- An integrated OIR System can achieve the best science when it engages a broad population of astronomers to pursue a diversity of science and scientific approaches.
- Federal investment in LSST follow-up capabilities and in community-prioritized instrumentation across the OIR System will help to maximize scientific output.

- Federal support to sustain technology, instrumentation, and software development, and expertise in these fields, is necessary to optimize future science returns.

This report highlights some of the progress on science questions raised by the NRC decadal surveys *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) and *Vision and Voyages for Planetary Science in the Decade 2013-2022*[2] (VVPS), the existing facilities and capabilities, and the human resources that make up the U.S. OIR astronomical enterprise. The report then considers the science that will be enabled by new instruments and facilities. It highlights the critical OIR instruments that are necessary in the near term to achieve decadal objectives, enable innovative research, and augment LSST with follow-up observations. It then addresses how to optimize scientific return from available resources through cooperation among public and private observatories.

The committee's top-level recommendations are presented here in priority order, driven by the statement of task (see Preface) and motivated by the guiding principles above. The committee did not have a budget or guidelines for funding; these recommendations are based on science considerations and provided as advice for the National Science Foundation (NSF), the sponsor requesting the report. The accompanying descriptions and justifications for the recommendations are in subsequent chapters.[3]

The committee's highest priority is a U.S. OIR System that is well coordinated and facilitates broad access to achieve the best science. Broad access at non-federal telescopes can be accomplished in a number of creative ways, including, but not limited to, engaging in limited term partnerships for partnering on telescopes, instruments, and data; bartering time on one facility for another; and swapping instruments.

RECOMMENDATION 1. The National Science Foundation (NSF) should direct the National Optical Astronomical Observatory to administer a new telescope time exchange with participating observatories of the U.S. Optical and Infrared System. Observatory representatives would barter facilities, swap instruments, or engage in limited term partnerships for telescope time or data access on behalf of their respective constituencies, as appropriate, and NSF would barter telescope time or data access or engage in limited term

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C.

[2] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C.

[3] For convenience, all of the conclusions and recommendations that appear in individual sections are listed in the Epilogue in order of appearance.

partnerships to carry out proposals competed through a system-wide time allocation committee. (Chapter 6)

Maximum returns from federal investment will be achieved when the community has the capabilities necessary to address the decadal science priorities. Those capabilities include not only existing ones but also new ones that are developed as the science evolves. The decadal surveys identify long-term goals for community facilities, but capabilities needed in the short term, particularly in rapidly evolving areas of research, would benefit from shorter planning timescales. Achieving these capabilities through coordination or partnerships can be accomplished by establishing at the national level an ongoing planning process that will engage the entire OIR user community in identifying and realizing small- and medium-scale projects and programs between decadal and mid-decadal reviews.

RECOMMENDATION 2. The National Science Foundation should direct the National Optical Astronomical Observatory (NOAO) to administer an ongoing community-wide planning process to identify the critical Optical and Infrared System capabilities needed in the near term to realize the decadal science priorities. NOAO could facilitate the meeting of a system organizing committee, chosen to represent all segments of the community, which would produce the prioritized plan. NSF would then solicit, review, and select proposals to meet those capabilities, within available funding. (Chapter 6)

As a start in the OIR System planning, and as charged, the committee has in this report identified a number of instrumentation and coordination requirements that would enhance the science output from medium (3.5- to 5-meter) and large (6- to 12-meter) telescopes, including augmenting LSST data once they come online.

RECOMMENDATION 3. The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way. (Chapter 5)

LSST, the top-ranked, large, ground-based facility recommended in NWNH and highly ranked in VVPS, will enable a broad range of science across the community. The science returns will be even greater through complementary and supplementary work at other facilities. Recommendations 4a-4d target the optimization of science from data obtained with LSST. The large number of transient events that will be detected nightly by LSST will require a software event broker system to identify significant objects that need spectroscopic and higher-cadence photometric follow-up. Coordination of federally supported facilities and capabilities in the Southern Hemisphere will enable a rapid response to these events and therefore promote maximum scientific productivity.

RECOMMENDATION 4a. The National Science Foundation should help to support the development of event brokers, which should use standard formats and protocols, to maximize Large Synoptic Survey Telescope transient survey follow-up work. (Chapter 5)

RECOMMENDATION 4b. The National Science Foundation should work with its partners in Gemini to ensure that Gemini South is well positioned for faint-object spectroscopy early in the era of Large Synoptic Survey Telescope operations, for example, by supporting the construction of a rapidly configurable, high-throughput, moderate-resolution spectrograph with broad wavelength coverage. (Chapter 5)

RECOMMENDATION 4c. The National Science Foundation should ensure via a robustly organized U.S. Optical and Infrared (OIR) System that a fraction of the U.S. OIR System observing time be allocated for rapid, faint transient observations prioritized by a Large Synoptic Survey Telescope event broker system so that high-priority events can be efficiently and rapidly targeted. (Chapter 5)

RECOMMENDATION 4d. The National Science Foundation should direct its managing organizations to enhance coordination among the federal components of medium- to large-aperture telescopes in the Southern Hemisphere, including Gemini South, Blanco, the Southern Astrophysical Research (SOAR) telescope, and the Large Synoptic Survey Telescope (LSST), to optimize LSST follow-up for a range of studies. (Chapter 5)

Looking to the future, it is beneficial for NSF and the community to consider facilities and technologies that will bring the greatest scientific return for the investment. The largest telescopes, the Giant Segmented Mirror Telescopes (GSMTs), are being constructed by private and international partners. It is important for a broad U.S. community to have direct access to the GSMTs through federal investment so that the best science can be achieved.

RECOMMENDATION 5. The National Science Foundation should plan for an investment in one or both Giant Segmented Mirror Telescopes in order to capitalize on these observatories' exceptional scientific capabilities for the broader astronomical community in the Large Synoptic Survey Telescope era, for example, through shared operations costs, instrument development, or limited term partnerships in telescope or data access or science projects. (Chapter 4)

Many types of technologies are in various stages of development. Adaptive optics (AO), for example, has become a mainstay of telescopes but needs more investment in order for AO-assisted telescopes to achieve the most stable images with the best possible resolution; detector technology continues to improve. Sustaining technological developments and maintaining U.S. expertise in instrumentation and software are important for remaining competitive in the rapidly advancing world stage of OIR astronomy.

RECOMMENDATION 6. The National Science Foundation (NSF) should continue to invest in the development of critical instrument technologies, including detectors, adaptive/active optics, and precision radial velocity measurements. NSF should also use existing instrument and research programs to support small-scale exploratory programs that have the potential to develop transformative technologies. (Chapter 4)

RECOMMENDATION 7. The National Science Foundation (NSF) should support a coordinated suite of schools, workshops, and training networks run by experts to train the future generation of astronomers and maintain instrumentation, software, and data analysis expertise. Some of this training might best be planned as a sequence, with later topics building on earlier ones. NSF should use existing instrument and research programs to support training to build instruments. (Chapter 3)

There are a number of important topics for which the committee has reached conclusions but not recommendations. Among these are conclusions regarding data archives and their public availability and means of access (Section 3.3), the Dark Energy Camera (DECam) and Dark Energy Spectroscopic Instrument (DESI) (Section 5.1), the Mid-Scale Innovations Program (MSIP) structure (Section 6.3), and international discussions (Section 6.5).

1

Introduction

This report outlines a new vision of the nighttime U.S. Optical and Infrared (OIR) System to achieve the science objectives of the decadal priorities and to optimize the science return on federal and non-federal investments. For context, it is instructive to reflect on the status of the OIR System at the time of the National Research Council's (NRC's) 1995 McCray report, *A Strategy for Ground-Based Optical and Infrared Astronomy,*[1] and the similarities between the concerns of the U.S. community then and now. Twenty years ago, 80 percent of the total aperture area of telescopes was held privately, and 50 percent of U.S. astronomers relied solely on National Optical Astronomy Observatory (NOAO) facilities for telescope access. At the time, those NOAO facilities included the Mayall 4-meter at Kitt Peak National Observatory (KPNO) in the Northern Hemisphere, the Blanco 4-meter at Cerro Tololo Inter-American Observatory (CTIO) in the Southern Hemisphere, and the NOAO portion of the Wisconsin-Indiana-Yale-NOAO (WIYN) Consortium 3.5-meter, plus a suite of smaller-aperture telescopes that are particularly useful for programs requiring more time than can generally be assigned to any single purpose on a large telescope. These include wide-field surveys, Ph.D. thesis-style projects, and time domain studies. In 1995, Gemini (an international entity that is not part of NOAO) was under construction; the McCray report recommended as its first priority the development of unique capabilities, with increased OIR funding to

[1] National Research Council (NRC), 1995, *A Strategy for Ground-Based Optical and Infrared Astronomy,* National Academy Press, Washington, D.C.

support Gemini operations and new instrumentation. With level funding, it was recommended that KPNO be de-prioritized.

Today, the U.S. portion of the Gemini North and South 8.1-meter telescopes provides the public, large-aperture component of the System, and roughly 50 percent of U.S. astronomers continue to rely predominantly on public access (i.e., do not have institutional access to a private medium- to large-aperture telescope). For telescopes with apertures of 2.0 meters or larger, currently 76 percent of the time is private—that is, not available to the entire community. The Large Synoptic Survey Telescope (LSST) is under construction and will be a central, public component of the OIR System in the decade of the 2020s, though it offers data rather than telescope access. Following the Portfolio Review Committee recommendations,[2] the KPNO Mayall 4-meter is facing divestiture by the National Science Foundation (NSF), but planning is under way for operations to be transferred to the Department of Energy for the Dark Energy Spectroscopic Instrument (DESI) project later this decade. The smaller-aperture KPNO telescopes, useful for surveys, time domain studies, and instruction, among other things, have also largely been removed from the open-access system.

Given limited resources, the McCray report recommended a new program to leverage private investments by publicly supporting instrumentation at private facilities, with the goals of ensuring the best science, providing public access to a broad range of facilities, and realizing cost savings through efficiencies. This idea was developed and modified by *Astronomy and Astrophysics in the New Millennium*,[3] resulting in the Telescope System Instrumentation Program (TSIP), which operated for 10 years. The McCray report also wrestled with whether instruments should be built in-house at NOAO, at universities, or in collaborations. These issues are all familiar today.

As the number of practitioners of astronomy has grown since the time of the McCray report (membership in the American Astronomical Society grew by 33% from 1990 to 2006, for example),[4] new participants among universities and research institutions—including foreign institutions—have emerged in the non-federal sector of U.S. telescopes and instruments. Partnerships among non-federal entities have flourished, especially over the past decade. With the largest telescopes in the non-federal sector, this has led to more restricted community access to frontier ground-based OIR telescopes and instrumentation. Despite the substantial growth

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[2] National Science Foundation, 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

[3] NRC, 2000, *Astronomy and Astrophysics in the New Millennium,* The National Academies Press, Washington, D.C.

[4] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C. Figure 4.11.

in the number of U.S. telescopes and instruments that are producing high-quality data for astronomical research, and the growth of non-federal investment, the giant telescopes being planned are not fully funded yet. In considering the overall context of U.S. ground-based OIR astronomy, this means there are significant opportunities for partnerships within the U.S. community.

NSF is a critical partner in ground-based astronomy in the United States, although its role within the existing ecosystem as leader, major or minor partner, or enabler, has varied over the years. With NSF support, Gemini is operating and has had several generations of instruments, the Very Large Array (VLA) has recently completed a major upgrade, and the Atacama Large Millimeter/submillimeter Array (ALMA) has come online. The Advanced Technology Solar Telescope (ATST), now the Daniel K. Inoue Solar Telescope (DKIST), and LSST are under construction, supported by the NSF Major Research Equipment and Facilities Construction (MREFC) line. There are two major impacts of these large construction and upgrade projects on the NSF Division of Astronomical Sciences (AST) budget: (1) the need to allocate operations funding for the new facilities from within current and future budgets and (2) the need to support research, both observational and theoretical, motivated and enabled by the resulting data. In preparing for the opportunities with the new facilities, NSF AST has had to plan for divestiture of several existing facilities that the agency has either partially or fully supported in the past. Even with divestiture, the success rate of research proposals both for technical development and for science is likely to stay quite low by historical standards. Furthermore, neither the presidential budget request nor congressional appropriations provide enough funding to carry out many of the highest priorities of the NRC's decadal surveys in astronomy and astrophysics.

Non-NSF federal support for ground-based astronomy includes investment by NASA, the Department of Energy (DOE), and the Smithsonian Institution in telescope access and instrumentation, which has greatly expanded research opportunities for the community. Nevertheless, the involvement of NASA and DOE in ground-based OIR is focused on particular fields of interest to their programs; mission-driven agency funding is not available across all fields of astronomy. In addition, the Air Force (Department of Defense) has provided some access in the past to a number of military telescopes and has supported Pan-STARRS development.

Progress on many scientific problems in astronomy increasingly relies on synergies between ground-based and space-based observations. This stems in part from the importance of multi-wavelength observations in understanding and interpreting astronomical phenomena. NASA's operating great observatories, the Hubble Space Telescope (HST), Fermi-GLAST, Chandra X-Ray Observatory, and Spitzer Space Telescope, plus smaller missions such as Kepler and now Kepler 2, NuSTAR, and Swift, provide important complementarity with ground-based OIR observations. OIR photometry, spectroscopy, and polarimetry in various forms are a mainstay in the characterization of astronomical objects, including those discovered at other wavelengths from space and on the ground. With new and planned NASA missions such as the Transiting Exoplanet Survey Satellite (TESS), the James Webb Space Telescope (JWST), the Wide-Field Infrared Survey Telescope (WFIRST), and European Space Agency missions Gaia and Euclid, this trend is expected to continue.

While the field of astronomy is driven by the existence of state-of-the-art facilities for collecting photons from astronomical sources, the prosecution of research in astronomy, and in particular the physical understanding of astronomical phenomena, requires in addition software, analysis techniques, scientific interpretation, theoretical work, and numerical simulations (the latter two are not considered in this report). Moreover, scientists having various skill sets are needed in all phases of astronomy research: theory, design, implementation, execution, and interpretation. Future progress in astronomy will rely critically on the training, promotion, and retention of creative people.

The question before the committee is how to optimize ground-based optical and infrared astronomy research with the given resources by means of judicious investment and collaborations. This report summarizes the issues and provides some recommendations for achieving science objectives and improving the effectiveness of the U.S. OIR System.

Chapter 2 describes recent decadal science achievements in the OIR and overlapping research with other wavelength regimes on the ground and in space. Chapter 3 reviews the current U.S. public and private telescopes and instruments, summarizes the volume of research output based on their data, gives an overview of archives, and discusses training and the need for continued expertise in several key areas. Chapter 4 reviews the compelling science needs in terms of instrumentation and technology development as LSST and the giant telescopes come online, while Chapter 5 focuses on additional needs to enhance science from LSST data. Chapter 6 presents a revised U.S. OIR System that would entail a telescope time exchange program and a planning process for the community to advise on future needs within the context of the decadal surveys. Chapter 7 collects all the conclusions and recommendations from Chapters 2 through 6.

2

Science from Major U.S. Ground-Based OIR Investments

2.1 PROGRESS ON DECADAL SCIENCE PRIORITIES

The 2010 National Research Council (NRC) decadal survey report *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) laid out a broad program of astronomical research, within which it identified three overarching science themes as particularly ripe for exciting progress in the coming decade: Cosmic Dawn, New Worlds, and Physics of the Universe. Cosmic dawn involves searching for the first stars, galaxies, and black holes and understanding the formation and early evolution of structure in the universe. In the realm of new worlds, astronomers seek nearby habitable planets and explore properties of exoplanetary systems and their disk progenitors, probe the formation and evolution of stars including the Sun, and seek to understand the details of gas-stellar processes and star formation histories across the full range of galaxies including the Milky Way. The quest to understand basic scientific principles, including dark matter, dark energy, and the nature of gravity, make up the physics of the universe. The 2011 NRC decadal survey report *Vision and Voyages for Planetary Science in the Decade 2013-2022*[2] (VVPS) similarly provides a roadmap for study of the solar system, from the gas giants and rocky inner planets and their interiors, surfaces, and atmospheres, to moons and primi-

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C.

[2] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C.

tive bodies, in order to understand their origins and evolution and the development of habitable environments.

Ground-based optical and infrared (OIR) astronomy facilities provide critical capabilities that are enabling major advances in all of these (as well as other) high-priority areas of research. Increasingly, progress in these subjects requires observations across the electromagnetic spectrum and thus entails multi-wavelength campaigns that make use of both ground-based and space-based facilities. The focus of this chapter is on the key roles that ground-based OIR facilities play in this science as well as the important synergies with observations at other wavelengths and in space. With more than 2,000 publications annually based on data from telescopes in the U.S. OIR System, it is not possible to review all of the exciting recent discoveries and breakthroughs, so instead a few highlights are presented to illustrate the breadth of the accomplishments and the progress being made on some of the key decadal science themes.

A key goal of cosmic dawn research is to understand the first galaxies and their role in emitting ultraviolet radiation that reionized the universe during the first billion years after the Big Bang. Recent observing campaigns with the Hubble Space Telescope (HUDF12, CANDELS, BoRG, CLASH, HFF)[3] with longer wavelength constraints based on Spitzer Space Telescope observations have pushed the high-redshift frontier to the epoch when the universe was about 500 million years old (redshift $z \sim 10$),[4] providing the first glimpses into the nature of the galaxy population at these very early times.[5] Detailed studies of these early galaxies require ground-based spectroscopy; the Magellan telescopes have been used in recent years to provide the first spectroscopic confirmation of galaxies seen when the universe was less than 800 million years old ($z \sim 7$-7.5).[6] The record for the most distant quasar ($z = 7.09$, 770 million years)[7] has been pushed to the same epoch, using near-infrared (IR) and optical imaging from the United Kingdom Infrared Telescope (UKIRT) and the Sloan Digital Sky Survey (SDSS) and detailed spectroscopy from Gemini North and the ESO Very Large Telescope (VLT). Recent Magellan observa-

[3] Acronyms, especially those denoting individual instruments and missions, are defined in Appendix C.

[4] D. Coe, A. Zitrin, M. Carrasco, X. Shu, W. Zheng, M. Postman, L. Bradley, A. Koekemoer, R. Bouwens, T. Broadhurst, A. Monna, et al., 2013, CLASH: Three strongly lensed images of a candidate z 11 galaxy, *The Astrophysical Journal* 762:32.

[5] P.A. Oesch, R.J. Bouwens, G.D. Illingworth, I. Labbé, M. Franx, P.G. van Dokkum, M. Trenti, M. Stiavelli, V. Gonzalex, and D. Magee, 2013, Probing the dawn of galaxies at z ~ 9-12: New constraints from HUDF12/XDF and CANDELS data, *The Astrophysical Journal* 773:75.

[6] J.E. Rhoads, P. Hibon, S. Malhotra, M. Cooper, and B. Weiner, 2012, A Lyα galaxy at redshift z = 6.944 in the cosmos field, *The Astrophysical Journal Letters* 752(2):L28.

[7] D.J. Mortlock, S.J. Warren, B.P. Venemans, M. Patel, P.C. Hewitt, R.G. McMahon, C. Simpson, T. Theuns, E.A. Gonzáles-Solares, A. Adamson, S. Dye, et al., 2011, A luminous quasar at a redshift of z = 7.085, *Nature* 474(7353):616-619.

tions of Lyman-alpha absorption in the spectra of $z \sim 6$ quasars[8] found by surveys such as SDSS indicate that reionization is completed by $z \sim 5$. The origin of black holes and their connection to galaxy formation is another focus of Cosmic Dawn. A spectroscopic survey of 700 nearby galaxies using the Hobby-Eberly telescope finds several galaxies with unusually massive black holes that do not follow the usual black hole mass-galaxy mass scaling relation.[9]

In the realm of new worlds, NWNH recommended a multi-pronged approach to taking a census of habitable worlds around other stars. In the past few years, several candidates for potentially habitable planets have been found both from ground-based radial velocity surveys and from NASA's Kepler mission, including eight small planets orbiting G-type stars like the Sun.[10] Another exoplanet, Kepler-186f (Figure 2.1) was inferred to be Earth-sized and orbiting within its M dwarf star's habitable zone.[11] Observations with adaptive optics on Keck and speckle imaging on Gemini telescopes ruled out the possibility of a faint companion star mimicking the observed light curve dip, although Kepler observations supplemented by high-spatial-resolution speckle imaging on National Optical Astronomical Observatory's (NOAO's) Wisconsin-Indiana-Yale-NOAO Consortium 3.5-m telescope (WIYN) and Gemini telescopes have revealed that about half of exoplanet hosts are binary star systems.[12] Ground-based follow-up spectroscopy on telescopes throughout the U.S. OIR System to characterize stellar hosts and measure precise radial velocities remains critical for fully exploiting the data from present and future transiting planet detection missions.

The characterization of exoplanet atmospheres using transit techniques on both ground- and space-based telescopes has made substantial advances; the detection of emitted light and molecular absorption by giant planets close to their host stars has now been made in a number of systems. The recent deployment of the Gemini Planet Imager (GPI) adaptive optics (AO) system on Gemini South, SPHERE on the European Southern Observatory (ESO) VLT, Keck AO, the SEEDS[13] project

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[8] G.D. Becker, J.S. Bolton, P. Madau, M. Pettini, E.V. Ryan-Weber, and B.P. Venemans, 2014, Evidence of patchy hydrogen reionization from an extreme Lyα trough below redshift six, *Monthly Notices of the Royal Astronomical Society* arXiv:1407.4850 [astro-ph.CO].

[9] R.C.E. van den Bosch, K. Gebhardt, K. Gültekin, G. van de Ven, A. van der Wel, and J.L. Walsh, 2012, An over-massive black hole in the compact lenticular galaxy NGC 1277, *Nature* 491(7426):729-731.

[10] NASA Exoplanet Archive, http://exoplanetarchive.ipac.caltech.edu/, accessed February 1, 2015.

[11] E.V. Quintana, T. Barclay, S.N. Raymond, J.F. Rowe, E. Bolmont, D.A. Caldwell, S. B. Howell, S.R. Kane, D. Huber, J. R. Crepp, and J. J. Lissauer, 2014, An Earth-sized planet in the habitable zone of a cool star, *Science* 344(6181):277-280.

[12] E.P. Horch, S.B. Howell, M.E. Everett, and D.R. Ciardi, 2014, Most sub-arcsecond companions of Kepler exoplanet candidate host stars are gravitationally bound, *The Astrophysical Journal* 795(1):60.

[13] National Astronomical Observatory of Japan, Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS) Project, http://esppro.mtk.nao.ac.jp/eng/seeds, accessed February 1, 2015.

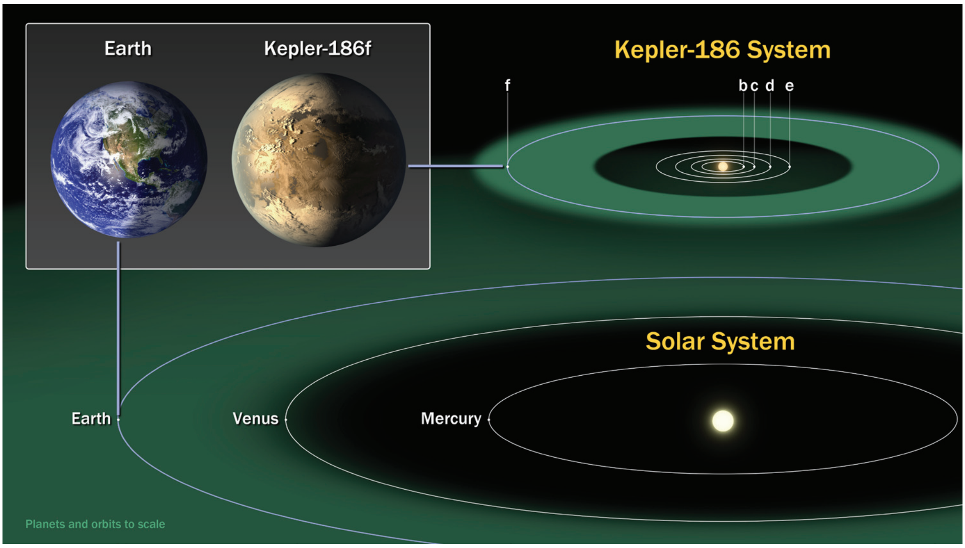

FIGURE 2.1 Kepler 186 system, with five planets orbiting an M dwarf, compared with the solar system. Kepler 186-f lies in its star's habitable zone. SOURCE: Courtesy of NASA/Ames/Jet Propulsion Laboratory-Caltech/T. Pyle.

on Subaru, and Large Binocular Telescope (LBT) surveys LBTI and LEECH[14] are enabling direct high-contrast imaging of planets around bright stars, such as Beta Pictoris b (Figure 2.2), and will enable a census of outer planets around young stars. These OIR observations are now being complemented by Atacama Large Millimeter/submillimeter Array (ALMA), which is finding regions in the disks around young stars that likely were swept clear by newly formed planets.

Ground-based OIR surveys offer powerful probes of the physics of the universe. The Baryon Oscillation Spectroscopic Survey (BOSS) galaxy redshift survey, part of SDSS-III using the Sloan 2.5-meter telescope, has made measurements of the baryon acoustic oscillation (BAO) feature in galaxy clustering that determine the cosmic distance scale with precision at the percent level. In combination with cosmic microwave background anisotropy data from the Planck Surveyor and

[14] LBTI HOST (W. Danchi, V. Bailey, G. Bryden, D. Defrère, C. Haniff, P. Hinz, G. Kennedy, B. Mennesson, R. Millan-Gabet, G. Rieke, A. Roberge, et al., 2014, The LBTI hunt for observable signatures of terrestrial systems (HOSTS) survey: A key NASA science program on the road to exoplanet imaging missions, *Proceedings of the SPIE* 9146, Optical and Infrared Interferometry IV, 914607); LEECH (A. Skemer, D. Apai, V. Bailey, B. Biller, M. Bonnefoy, W. Brandner, E. Buenzli, L. Close, J. Crepp, D. Defrere, S. Desidera, et al., 2013, LEECH: A 100 night exoplanet imaging survey at the LBT, *Proceedings of the International Astronomical Union* 8(S299):70-71) surveys.

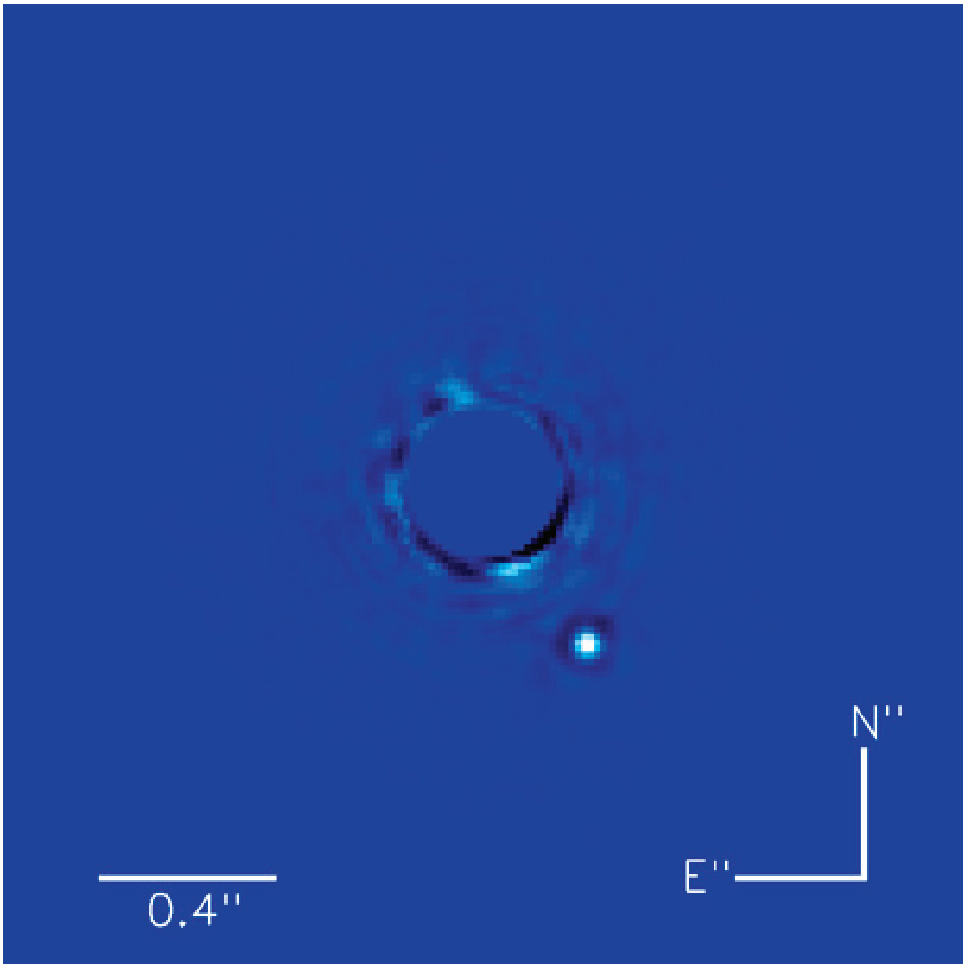

FIGURE 2.2 Image from GPI on Gemini South of Beta Pictoris b, a planet orbiting the star Beta Pictoris (masked out in the center of the image). SOURCE: Courtesy of Gemini Observatory/Association of Universities for Research in Astronomy/Processing by Christian Marois, National Research Council Canada.

ground- and space-based measurements of Type Ia supernovae, these results place high-precision constraints on cosmological parameters. This study is being continued in the extended BOSS (eBOSS) in SDSS-IV.

In 2013, the 5-year Dark Energy Survey (DES) began operation using the Dark Energy Camera on the NOAO Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (CTIO). A forerunner of the Large Synoptic Survey Telescope (LSST), DES will map 300 million galaxies (Figure 2.3) and measure

FIGURE 2.3 NGC 1398, a spiral galaxy in the Fornax cluster imaged with the Dark Energy Camera (DECam), is one of 300 million galaxies that will be imaged by the Dark Energy Survey. SOURCE: Courtesy of the Dark Energy Survey.

3,500 Type Ia supernovae to probe the accelerated expansion of the universe. Now in its second year, the survey has, among its initial results,[15] discovered 1,000 high-redshift supernovae and scores of high-redshift galaxy clusters, made weak-lensing maps of clusters, discovered new outer solar system bodies, and discovered ultra-faint dwarf galaxies that may account for some local dark matter.[16] These projects will be complemented by the Hobby-Eberly Telescope Dark Energy Experiment[17] (HETDEX), which should begin taking BAO spectroscopic data of a million galaxies with a massively replicated integral field unit (IFU) system in 2015.

In the realm of solar system studies envisioned by VVPS, Keck and Gemini carried out complementary infrared (1-4 micron) studies of three successive violent

[15] The Dark Energy Survey, http://www.darkenergysurvey.org, accessed February 1, 2015.

[16] S.E. Koposov, V. Belokurov, G. Torrealba, and N. Wyn Evans, 2015, Beasts of the southern wild. Discovery of a large number of ultra faint satellites in the vicinity of the Magellanic clouds, submitted to *The Astrophysical Journal* arXiv:1503.02079 [astro-ph.GA]; and K. Bechtol, A. Drlica-Wagner, E. Balbinot, A. Pieres, J.D. Simon, B. Yanny, B. Santiago, R.H. Wechsler, J. Frieman, A.R. Walker, P. Williams, E. Rozo, E.S. Rykoff, A. Queiroz, E. Luque., et al., 2015, Eight new Milky Way companions discovered in first-year Dark Energy Survey data, submitted to *The Astrophysical Journal* arXiv:1503.02584 [astro-ph.GA].

[17] The Hobby-Eberly Telescope Dark Energy Experiment, http://hetdex.org/, accessed February 1, 2015.

volcanic eruptions on Jupiter's moon Io, which were more massive and frequent than previously expected. This work provides insights into Io's thermal processes.[18] The NASA Dawn mission achieved orbit around the dwarf planet Ceres in March 2015 in order to study its differentiation and composition. This study, along with Dawn's mapping of Vesta in 2011, provides important perspectives for ground-based OIR characterizations of Kuiper Belt objects. Dynamical cloud features on Saturn, Neptune, and Uranus have been studied with adaptive optics on telescopes such as Keck, Gemini, and Subaru.[19]

Trans-Neptunian Objects (TNOs), which are primitive bodies that provide insight on conditions in the early solar system, have been the subject of many ground- and space-based surveys to understand their properties and distribution.[20] The Next Generation Virgo Cluster Survey, a high-resolution study using the MegaPrime camera on the CFHT 3.6-meter telescope, discovered nearly 100 new objects, including a very distant TNO that suggests an extensive population of more than 11,000 such objects in the inner Oort Cloud.[21]

2.2 POSITIONING THE OIR SYSTEM TO COMPLEMENT NON-OIR ASTRONOMY

OIR astronomy spans only a few octaves of the electromagnetic spectrum, but often anchors astronomy that originates at other wavelengths. It is no accident that the human eye is tuned to detect starlight. Setting aside the cosmic microwave background, most of the light in the universe is starlight, and the infrared background is largely radiation from dust heated by stars. X-ray astronomers and radio astronomers need to know what kind of optical and infrared light is associated with their sources in order to understand their nature. A growing trend in astronomical research is the synergy between observations with different telescopes and instruments in the study of astrophysical phenomena. This includes coordinated use of multiple ground-based OIR facilities with complementary capabilities, use of OIR facilities in combination with ground-based observations at other wavelengths,

[18] I. de Pater, A.G. Davies, A. McGregor, C. Trujillo, M. Ádámkovics, G.J. Veeder, D.L. Matson, G. Leone, and the Gemini Io Team, 2014, Global near-IR maps from Gemini-N and Keck in 2010, with a special focus on Janus Patera and Kanehekili Fluctus, *Icarus* 242:379-395.

[19] H.B. Hammel, M.L. Sitko, D.K. Lynch, G.S. Orton, R.W. Russell, T.R. Geballe, and I. de Pater, 2007, Distribution of ethane and methane emission on Neptune, *The Astronomical Journal* 134(2):637.

[20] E. Vilenius, C. Kiss, T. Müller, M. Mommert, P. Santos-Sanz, A. Pál, J. Stansberry, M. Mueller, N. Peixinho, E. Lellouch, S. Fornasier, et al., 2014, "TNOs are cool": A survey of the trans-Neptunian region, *Astronomy and Astrophysics* 564(A35):1-18.

[21] Y.-T. Chen, J.J. Kavelaars, S. Gwyn, L. Ferrarese, P. Côté, A. Jordán, V. Suc, J.-C. Cuillandre, and W.-H. Ip, 2013, Discovery of a new member of the inner Oort cloud from the next generation Virgo cluster survey, *The Astrophysical Journal* 775:L8.

and use of OIR facilities in combination with space-based facilities. In the era of LSST, this trend will expand tremendously; follow-up of objects discovered by LSST will be important at many ground- and space-based astronomical facilities in the decade of the 2020s. A ground-based OIR strategy must mesh with developments beyond the OIR spectral range. This section mentions some of the ground-based OIR capabilities that are in use now or will be needed in the future to maximize science from observations at other wavelengths. Section 4.1 addresses more details of the OIR instrumentation, with conclusions and recommendations in Chapters 4 and 5.

Radio and Submillimeter Studies

The National Radio Astronomy Observatory (NRAO) scientific staff and NRAO User Committee identified a number of OIR capabilities important to radio, millimeter, and submillimeter (RMS) studies in achieving the goals of NWNH (using an NRAO poll for this report).[22] Studies of disk gaps formed by planetesimals, disk kinematics, and disk chemistry in protoplanetary disks, accretion and infall in young stellar objects, and gas-giant exoplanets all require OIR imaging capabilities with resolutions better than about 0.1 arcsecond to match the VLA and ALMA, with a field of view (FOV) of approximately 3 arcminutes. Such capabilities are important for studying galaxies too; for example, ALMA and the VLA observed a pair of gravitationally lensed merging galaxies at high redshift that were subsequently studied using Hubble Space Telescope (HST) and the Keck 10-meter with adaptive optics.[23]

The infrared sensitivity to warmer material complements the radio/submillimeter sensitivity to cold material, providing a complete picture of the constituents of these systems. Radio-variable objects identified in radio time domain surveys, such as M stars, active galactic nuclei (AGN) flares, and gamma-ray bursts (GRBs), need rapid OIR follow-up to allow identification with optical counterparts and characterization. A spectrograph with very wide wavelength coverage (from the blue end of optical light through the near-IR, like ESO's X-shooter), giving as many diagnostics as possible in a single observation, would be ideal.

The NRAO User Committee[24] made two specific suggestions for augmenting Gemini South:

[22] Tony Beasley, National Radio Astronomy Observatory, presentation to the committee on August 1, 2014.

[23] H. Messias, S. Dye, N. Nagar, G. Orellana, R.S. Bussmann, J. Calanog, H. Dannerbauer, H. Fu, E. Ibar, A. Inohara, R.J. Ivison, et al., 2014, Herschel-ATLAS and ALMA HATLAS J142935.3-002836, a lensed major merger at redshift 1.027, *Astronomy and Astrophysics* 568(A92):1-20.

[24] Tony Beasley, National Radio Astronomy Observatory, presentation to the committee on August 1, 2014.

1. An integral field spectrograph with an FOV of at least 1 arcminute, similar to the Denspak instrument of WIYN (no longer available), ESO's Multi-Unit Spectroscopic Explorer (MUSE), and the Keck Cosmic Web Imager (KCWI), would enable the study of ionized emission lines in starburst galaxies and the characterization of outflows and shocks, using optical emission line tracers in concert with molecular line tracers from ALMA.
2. A high-throughput multi-object spectrograph with a 5-10 arcminute FOV, similar to the Deep Imaging Multi-Object Spectrograph (DEIMOS) on Keck, would provide characterization of the faint centimeter-wave radio source population, both in terms of its makeup (fractions of star-forming galaxies and AGNs, both radio-quiet and radio-loud) and its redshift distribution. This is particularly important for future radio surveys with, for example, the Square Kilometer Array (SKA), which seek to use radio sources for constraining cosmology through clustering and radio weak lensing. Although getting a redshift for every galaxy in a radio survey would be prohibitively expensive, an accurate redshift *distribution* would be very useful, both for statistical applications and for validating photometric redshifts.

X-Ray and Gamma Ray Studies

Much of the science carried out with NASA's Chandra X-ray Observatory and the Nuclear Spectroscopic Telescope Array (NuSTAR) depends upon OIR capabilities for a wide range of complementary observations. These include direct imaging weak-lensing studies of clusters of galaxies to determine the total mass fraction of hot gas and multi-object spectroscopy to determine cluster membership. Deep IR spectroscopy will characterize high redshift and heavily obscured active galactic nuclei (AGNs) and quasars, while multi-epoch spectroscopy will constrain accretion disk models of their variability. IFU spectroscopy of nearby galaxies is needed to study winds and feedback in nearby star-forming galaxies and AGNs. The combination of X-ray observations with optical transients discovered in wide-field synoptic surveys will help discriminate among progenitor models for supernovae. As in the radio regime, wide-field multi-object spectroscopy is needed to identify and characterize sources such as AGNs and galaxy clusters found in deep X-ray surveys. These studies will be complemented by the Astro-H mission to be launched by the Japan Aerospace Exploration Agency in 2016, with NASA contributing a high-resolution soft X-ray spectrometer for measuring gas near black holes, active galaxies, and supernovae.

The European Space Agency's (ESA's) Athena X-ray mission, scheduled to launch in 2028, will yield high signal-to-noise spectra of AGNs and clusters of galaxies. NASA is expected to play a substantial role in Athena, and U.S. astronomers will consequently have access to Athena data. Ground-based OIR observations needed to complement Athena will be similar to those that presently complement Chandra. Conversely, Athena has a goal of a 2-hour response to targets of opportunity, many of which might be expected to come from LSST.

Gamma ray bursts detected by NASA's Swift and Fermi satellites require contemporaneous OIR imaging and spectroscopy to elucidate the connection between GRBs and supernovae. A gamma-ray flare in the Crab Nebula was followed up with the VLA, Keck Observatory, and Chandra X-ray observations to study details of the synchrotron emission associated with the nebula (see Figure 2.4).[25] Gamma-ray emission from novae and recurrent novae, discovered with Fermi[26] and studied with Swift, also require OIR follow-up observations.

There does not appear to be an outstanding unmet need for a specific ground-based OIR capability to complement present X-ray and gamma-ray missions, nor would planned missions appear to require more than the generic capabilities likely to be implemented over the course of the next decade.

Gravitational Wave Studies

Gravitational waves are perturbations in spacetime caused by accelerating masses, just as electromagnetic waves are emitted by accelerating charges. The first science data from the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) is expected in 2015. LIGO will work in concert with the Virgo interferometer in Italy. There are two approaches to ground-based OIR cross-identification. The first involves prompt searches with wide-field telescopes for LIGO-triggered events. Subsequent spectroscopic follow-up would be similar to GRB and supernova follow-up. The second involves optical triggering, with regular monitoring (at least nightly, perhaps more often) of the 5,000 or so nearest galaxies, which are the ones most likely to harbor detectable events. This would probably require facilities much like those of the Las Cumbres Observatory Global Telescope (LCOGT) network. Such monitoring would permit the post hoc search of LIGO data for optically triggered events.[27]

[25] M.C. Weisskopf, A.F. Tennant, J. Arons, R. Blandford, R. Buehler, P. Caraveo, C.C. Cheung, E. Costa, A. De Luca, C. Farrigno, H. Fu, et al., 2013, Chandra, Keck, and VLA observations of the Crab Nebula during the 2011 April gamma-ray flare, *The Astrophysical Journal* 765(1):56.

[26] M. Ackermann, M. Ajello, A. Albert, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi, R.D. Blandford, E.D. Bloom, et al., 2014, Fermi establishes a classical novae as a distinct class of gamma-ray sources, *Science* 345(6196):554-558.

[27] L.P. Singer, L.R. Price, B. Farr, A.L. Urban, C. Pankow, S. Vitale, J. Veitch, W.M. Farr, C. Hanna, K. Cannon, T. Downes, et al., 2014, The first two years of electromagnetic follow-up with advanced LIGO and Virgo, *The Astrophysical Journal* 795(2):105.

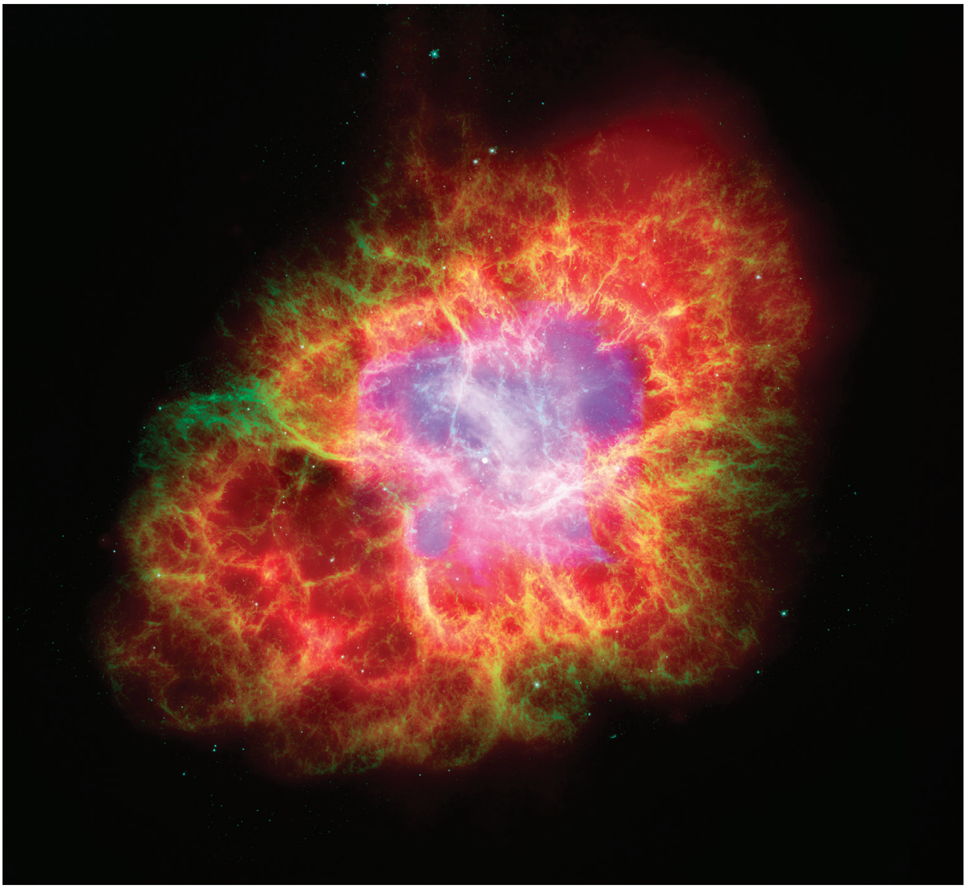

FIGURE 2.4 The Crab Nebula, shown as a composite with images from the Chandra X-ray satellite (blue), Spitzer Space Telescope (red), and Hubble Space Telescope (green). SOURCE: Courtesy of NASA/Jet Propulsion Laboratory-Caltech/European Space Agency/Chandra X-ray Center/University of Arizona/University of Szeged.

Technology for a future ESA space mission to detect gravitational waves will be tested with a planned launch of the LISA Pathfinder (named after a previously planned mission, the Laser Interferometer Space Antenna) in 2015. As an example of gravitational waves that might be detected, a recent study using the Gemini multi-object spectrograph (GMOS) on Gemini North and the Blue Channel spectrograph on the MMT (formerly the Multiple Mirror Telescope) found that what was thought for the past 30 years to be a binary system consisting of a white dwarf and an

M dwarf instead was a white dwarf binary system.[28] These white dwarf binary stars are spiraling inward and should eventually merge, producing gravitational waves.

2.3 FUTURE SYNERGIES BETWEEN GROUND-BASED AND SPACE-BASED OIR FACILITIES

Powerful science comes from combining space-based observations with data from the OIR System. This combination has proved profoundly productive—sensitive imaging from unique instruments in space combined with imaging surveys and spectra from large telescopes on the ground has revealed the nature of faint objects both near (such as field brown dwarfs) and far (such as supernovae to trace the history of cosmic expansion). In the 1990s, the Hubble Space Telescope (HST), along with Keck, the Hobby-Eberly Telescope, Gemini, Magellan, and other large ground-based telescopes worked effectively to exploit these opportunities. In the 2020s, the James Webb Space Telescope (JWST) along with LSST and other large telescopes and the Giant Segmented Mirror Telescopes will combine to solve a new set of cosmic mysteries.

Gaia

One space observatory that will provide a rich source of scientific opportunities is the ESA satellite Gaia, launched in 2013. By the end of its mission, Gaia will have imaged a billion stars 70 times each to measure their brightnesses, colors, parallaxes, and motions. Gaia will determine the positions of stars brighter than 15th magnitude to 40 microarcseconds; this will provide parallax distances with 10 percent precision to almost 100 million stars in the Milky Way. European colleagues are already using ESO facilities to follow up 100,000 stars that represent various Milky Way populations.[29] Some of these will be individual targets, while others will need observations over wide fields to study clusters and coherent kinematic structures. Gaia has begun to report discoveries of transients, including supernovae, which demand prompt OIR follow-up spectroscopy.

[28] M. Kilic, W.R. Brown, A. Gianninas, J.J. Hermes, C.A. Prieto, and S.J. Kenyon, 2014, A new gravitational wave verification source, *Monthly Notices Letters of the Royal Astronomical Society* 444(1):L1-L5.

[29] G. Gilmore, S. Randich, M. Asplund, J. Binney, P. Bonifacio, J. Drew, S. Feltzing, A. Ferguson, R. Jeffries, G. Micela, I. Negueruela, et al., 2012, The Gaia-ESO public spectroscopic survey, *The Messenger* 147:25.

TESS

Another mission that will have rich interactions with ground-based OIR facilities is NASA's Transiting Exoplanet Survey Satellite (TESS). This Explorer-class mission is scheduled for launch in 2017. The principal goal of the TESS mission is to detect small planets with bright host stars in the solar neighborhood. TESS stars will be 30-100 times brighter than those surveyed by the Kepler satellite, so TESS planets should be far easier to characterize with follow-up observations. These follow-up observations, with JWST and with large ground-based telescopes, will provide refined measurements of the planets' masses, sizes, densities, and atmospheric properties. NASA is already planning a new precision radial velocity instrument for the WIYN 3.5-meter telescope as well as continued access to the much larger Keck telescope. The legacy of TESS will be a catalog of the nearest and brightest stars that host transiting exoplanets, which should be excellent targets for detailed investigations in the coming decades. The Kepler 2 mission of the Kepler spacecraft is providing a preview of TESS science and generating planet candidates along the ecliptic plane.

JWST

NASA's upcoming flagship astrophysics mission in space is JWST. This observatory will have a 6.5-meter aperture and will have passive cooling of the optics to a temperature of 39 K behind a large sunshield. An ambitious set of instruments using infrared array detectors will provide unprecedented sensitivity in the near- and mid-IR at the diffraction limit of about 0.1 arcsecond. The JWST project is working to a 2018 launch date. The scientific program of JWST will be exceptionally broad, and, like HST, it will open up a cornucopia of rewarding follow-up with complementary facilities on the ground, especially with the most sensitive OIR instruments. As noted in VVPS, JWST will be important for near- and mid-IR imaging and spectroscopy of solar system planets, particularly Neptune and Saturn, as well as smaller bodies such as comets and Kuiper Belt objects, and will complement several NASA planetary missions. NWNH highlights science priorities across astrophysics fields from protoplanetary and circumstellar disks and exoplanet atmospheres and surfaces, to star formation and galaxy evolution, to the early universe that will require JWST for near- and mid-IR imaging and spectroscopy. Science returns from JWST will be enhanced through complementary ground-based observations on large and giant telescopes in addition to LSST.

WFIRST

After JWST, NASA plans to focus on the Wide-Field Infrared Survey Telescope (WFIRST), the mission endorsed by NWNH as the top-ranked, large-scale, space-based priority for the coming decade. Assuming a 2017 start for WFIRST, the telescope could be operating in 2024. The present design takes advantage of a 2.4-meter telescope assembly that was built for another government agency but that has been transferred to NASA for this use. The main instrument is a wide-field detector array in the near-IR that can be used to obtain images and spectra. This mission will conduct a wide-field survey enabling a wide range of science, including investigations of dark energy using supernovae, weak lensing, and clusters of galaxies. Exoplanets will be detected by gravitational microlensing signals and probably directly imaged with a coronagraph. In addition, there will be a guest investigator program.

One interesting aspect of the planned work is that the WFIRST observations will overlap significantly with the areas studied by LSST. This overlap will provide the opportunity to use the optical data from the ground in conjunction with the near-IR for more reliable measurements of galaxy redshifts as well as enabling sophisticated reanalysis of the LSST data informed by the superior resolution of the space-based data. It also creates the possibility for WFIRST follow-up studies of transient events discovered from the ground.

Euclid

ESA aims to launch Euclid, an M-class (medium-scale) mission, in 2020. Its science mission is to probe dark matter and dark energy by mapping cosmic structure through weak gravitational lensing using optical imaging complementary to the near-IR imaging of WFIRST. Euclid will also obtain near-IR spectroscopy and photometry and study baryon acoustic oscillations in the near-IR using detectors provided by NASA. Like WFIRST, Euclid will be synergistic with LSST through observations of large-scale structure and variable sources.

3

The U.S. OIR System

3.1 CURRENT TELESCOPES AND INSTRUMENTS IN THE OPTICAL AND INFRARED SYSTEM

The U.S. Optical and Infrared (OIR) System is the term that has been adopted since the 2000 decadal survey, *Astronomy and Astrophysics in the New Millennium*[1] (AANM), for the joint set of astronomical capabilities, public and private, that is available to members of the U.S. astronomical community. The suite of facilities is strongly connected by means of the researchers who successfully make use of these capabilities to conduct world-leading astrophysical research. The telescopes that today constitute the OIR System range up to 10 meters in aperture and 11.8 meters in effective aperture, with current activities aimed at producing two new facilities in the 24- to 30-meter-aperture range. Smaller telescopes are an integral part of the OIR System, since astronomical research often depends on the use of telescopes of different sizes to address different aspects of a question most effectively. An additional component of the System is archival and survey data, the use of which is becoming increasingly important as large surveys continue.

Telescopes in the System

Within the OIR System, the National Science Foundation's (NSF's) assets are the National Optical Astronomy Observatory (NOAO) and the U.S. share of

[1] National Research Council (NRC), 2000, *Astronomy and Astrophysics in the New Millennium,* The National Academies Press, Washington, D.C.

the Gemini Observatory. NOAO is the U.S. national OIR observatory, operated as a federally funded research and development center by NSF, and includes the Kitt Peak National Observatory (KPNO) in Arizona and the Cerro Tololo Inter-American Observatory (CTIO) in Chile. NOAO currently provides open access to 4-meter-class telescopes, the Mayall 4-meter and the Wisconsin-Indiana-Yale-NOAO Consortium (WIYN) 3.5-meter in the north and the Blanco 4-meter and Southern Astrophysical Research (SOAR) 4.2-meter in the south. The Dark Energy Survey (DES), a project funded by the Department of Energy (DOE), NSF, and U.S. and foreign institutions, utilizes 30 percent of the time on the Blanco telescope for 5 years in exchange for having built the Dark Energy Camera (DECam). DOE is planning to build and operate the Dark Energy Spectroscopic Instrument (DESI) on the Mayall telescope starting late in this decade.

Beyond operating telescopes, NOAO has a System Science Center, with activities in software and archiving, support for U.S. users of the Gemini telescopes, the NOAO Time Allocation Committee (TAC), and various other activities associated with the OIR System and its evolution. Among these, NOAO ran the Telescope System Instrumentation Program (TSIP) for NSF during the decade of its activity, including soliciting and reviewing proposals from non-federal observatories to build instruments and provide open-access time and providing program management and reporting for those activities. The NOAO TAC routinely reviews proposals for open-access time on many different telescopes, including the U.S. fraction of time on Gemini. NOAO has organized a number of community-wide workshops and studies to understand what capabilities would be needed to carry out decadal survey science and how those capabilities could be provided. These include three public workshops on the entire OIR System as well as the more focused NOAO studies on Renewing Small Telescopes for Astronomical Research[2] (ReSTAR) and Access to Large Telescopes for Astronomical Instruction and Research[3] (ALTAIR), which looked at subsets of the telescopes in the OIR System. NOAO also held several community-wide workshops to plan instrumentation for Gemini and convened an OIR System Roadmap Committee,[4] which examined the demographics and dynamics of the OIR System.

The Gemini Observatory is an international OIR observatory comprising two 8.1-meter telescopes, one on Maunakea, Hawaii, and one on Cerro Pachon in Chile. NSF is now a 65.5 percent partner in Gemini and also serves as the executive agency for the Gemini partnership. The Gemini telescopes are modern

[2] National Optical Astronomy Observatory (NOAO), 2007, *Renewing Small Telescopes for Astronomical Research,* https://www.noao.edu/system/restar/files/ReSTAR_final_14jan08.pdf.

[3] NOAO, 2009, *Final Report of the Committee on Access to Large Telescopes for Astronomical Instruction and Research (ALTAIR),* https://www.noao.edu/system/altair/files/ALTAIR_Report_Final.pdf.

[4] NOAO, "Ground-based O/IR System Roadmap Committee," http://ast.noao.edu/about/committees/system-roadmap, accessed February 1, 2015.

telescopes optimized for infrared (IR) observations and are used predominantly in a queue-scheduled mode. The international Gemini Board makes the selection of instrumental capabilities with input from the international Gemini Science and Technology Advisory Committee, and instruments are designed and built by instrumentation groups in the Gemini partner countries.

The accounting of the contents of the U.S. OIR System outside the federal observatories is not trivial. Table 3.1 lists the telescopes that were considered for this study (2.0-meter or larger aperture), with the fraction of each that are included in the U.S. OIR System (available to proposers at U.S. institutions), as well as the fraction that is available for open-access, peer-reviewed proposals. Some of the open access is restricted to particular science goals. For example, NASA provides support for the Infrared Telescope Facility (IRTF) and the Keck Observatory, which have been important for planetary science observations. Inclusion in the category "open access" is limited to time granted through regular, long-term policies; specifically, residual promised time from the now-defunct TSIP and impromptu or occasional time trades are not included. It is also worth noting that several private telescopes, including Keck, Sloan Digital Sky Survey (SDSS), and the Las Cumbres Observatory Global Telescope (LCOGT), make some or all of their data public after a proprietary period. Many telescopes are operated on behalf of consortia that include foreign partners, and telescopes on foreign soil often must make a certain fraction of their time available to host country astronomers. The effective number of telescopes in each size range is listed. Note that most of them are at non-federal facilities.

These telescopes serve a large and diverse community of privileged users affiliated with institutions that have contributed to their construction, operation, or instrumentation. However, currently only a small fraction of the OIR System is open to observing proposals from all astronomers in the community regardless of their institutional affiliation (19%, 33%, and 8% for large, medium, and small telescopes, respectively). This access is associated with facilities funded by federal agencies, typically NSF but also including NASA and DOE. Figure 3.1 shows the cumulative number of telescopes as a function of aperture, based on the numbers from Table 3.1. While Table 3.1 and Figure 3.1 consider only telescopes with aperture of 2.0 meters or greater, there are also a number of smaller telescopes, some of which provide open access, such as the Small and Moderate Aperture Research Telescope System (SMARTS) telescopes at CTIO. In the Northern Hemisphere, the only open-access small telescope is IRTF, which has near- and mid-IR instrumentation available to the community.

Instruments in the System

The ground-based astronomical landscape includes a mix of facilities with varying sensitivity, field of view, spatial resolution, spectral resolution, wavelength

TABLE 3.1 Telescopes Considered by the Committee

	Observatory/Site	Aperture	U.S. Fraction	Open Fraction
Large Telescopes (6-12 meters)				
Large Binocular Telescope (LBT)	Mt. Graham, Arizona	11.8[a]	0.50	0.00
Keck 1	Maunakea, Hawaii	10.0	1.00	0.17
Keck 2	Maunakea, Hawaii	10.0	1.00	0.17
Hobby-Eberly Telescope (HET)	McDonald Observatory, Texas	9.2	0.89	0.00
South African Large Telescope	South African Astronomical Observatory, Sutherland, South Africa	9.2	0.40	0.00
Subaru	Maunakea, Hawaii	8.3	0.10	0.00
Gemini N (Gillette)	Maunakea, Hawaii	7.9	0.69	0.60
Gemini S	Cerro Pachon, Chile	7.8	0.59	0.60
Magellan (Baade)	Las Campanas, Chile	6.5	0.90	0.00
Magellan (Clay)	Las Campanas, Chile	6.5	0.90	0.00
MMT	Mt. Hopkins, Arizona	6.5	1.00	0.00
Effective fractional number of telescopes			7.97	1.54
Medium Telescopes (3.5-5 meters)				
Hale Telescope	Palomar Observatory, California	5.1	1.00	0.00
Discovery Channel Telescope	Happy Jack, Arizona	4.3	1.00	0.00
SOAR	Cerro Pachon, Chile	4.2	0.70	0.30
Blanco Telescope	Cerro Tololo, Chile	4.0	0.90	0.90[b]
Mayall Telescope	Kitt Peak, Arizona	4.0	1.00	1.00
UKIRT	Maunakea, Hawaii	3.8	1.00	0.00
CFHT	Maunakea, Hawaii	3.6	0.20	0.00
ARC 3.5 m	Apache Point, New Mexico	3.5	1.00	0.00
WIYN	Kitt Peak, Arizona	3.5	1.00	0.40
Effective fractional number of telescopes			7.80	2.60
Small Telescopes (2-3 meters)				
Shane	Lick Observatory, Mt. Hamilton, California	3.0	1.00	0.00
IRTF	Maunakea, Hawaii	3.0	1.00	1.00
Harlan Smith	McDonald Observatory, Texas	2.7	1.00	0.00
DuPont	Las Campanas, Chile	2.5	0.90	0.00
Sloan Foundation (SDSS)	Apache Point, New Mexico	2.5	1.00	0.00[c]
Hiltner	Kitt Peak, Arizona	2.4	1.00	0.00
WIRO	Jelm Mtn., Wyoming	2.2	1.00	0.00
Bok	Kitt Peak, Arizona	2.2	1.00	0.00
UH 88-inch	Maunakea, Hawaii	2.2	1.00	0.00
Otto Struve	McDonald Observatory, Texas	2.1	1.00	0.00
KPNO 2.1 m	Kitt Peak, Arizona	2.1	1.00	0.00
LCOGT	Haleakala, Hawaii	2.0	0.75	0.00
LCOGT	Siding Spring, Australia	2.0	0.75	0.00
Effective fractional number of telescopes			12.40	1.00

[a] LBT is two coupled 8.4-meter telescopes with the equivalent area of a single 11.8-meter telescope.
[b] This is for pre- and post-DES.
[c] Sloan is a survey instrument; all Sloan Digital Sky Survey (SDSS) I-III data are now public.
NOTE: Acronyms are defined in Appendix C.

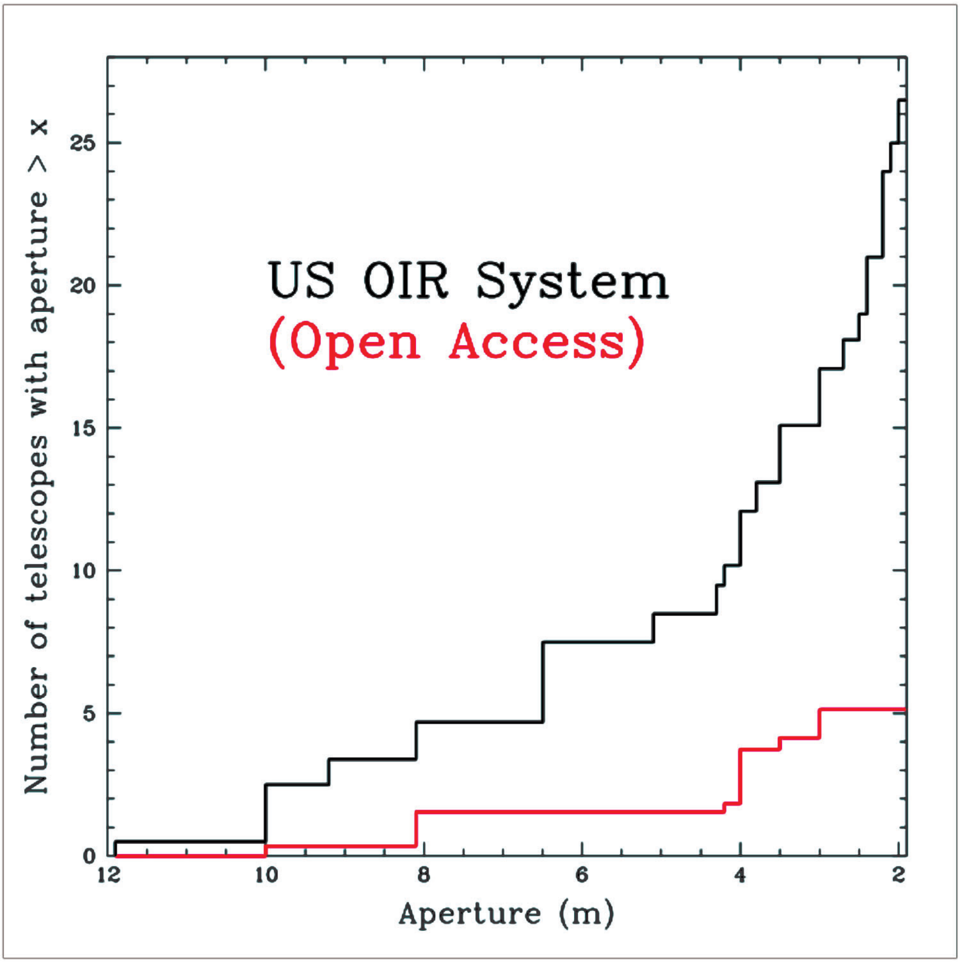

FIGURE 3.1 Number of telescopes with aperture greater than a given size, as a function of aperture. The black line shows the number in the system, including public and private facilities, while the red line shows the number publicly available.

coverage, and quality. Some instruments and even telescopes are quite specialized, while others are more general purpose. The demand for time on any particular telescope is a function of several of the above factors, as well as the special capabilities of the instrumentation and the match of the instrumentation to timely science. New instruments can make an otherwise obsolete telescope relevant again. State-of-the-art instrumentation is expensive, however, and limited resources must balance new needed capabilities against redundancy to address the level of demand.

The largest telescopes all carry sizable and diverse instrument complements, typically a mix of general-purpose and special-purpose capabilities. Optical and near-IR imaging and spectroscopy capabilities exist at almost every facility. Multi-object spectroscopy (MOS), integral field unit (IFU) spectroscopy, or both are often available. While there is duplication, there is also significant demand for the generic capabilities. Most of the largest telescopes have adaptive optics (AO) systems. Table 3.2 shows the distribution of these instrumental capabilities, classified into general categories for optical, near-IR, and mid-IR wavelength regimes, based on a survey sent to the individual observatories.

The medium- and smaller-aperture telescopes have become, in many cases, more specialized than in the past and relative to larger telescopes. They tend to have fewer instruments, tailored toward the unique strengths of each facility. The smaller telescopes are in some cases used for larger projects or surveys, but they also provide testbeds for new instrumentation and for more innovative operations strategies, such as remote or robotic operation. Smaller telescopes are also used for time domain studies, so are likely to be of value in the Large Synoptic Survey Telescope (LSST) era. For example, the SMARTS 1.5-m and the 1.3-m telescopes, accessible through the NOAO peer-review proposal process, are useful for transient studies and for synoptic observations.

A critical aspect of a System view of the facilities is the extent to which their development is planned and carried out in a way that acknowledges and takes advantage of the relationship among them. The past 20 years have seen sev-

TABLE 3.2 Instrumentation on 6- to 12-meter Telescopes

	Optical				Near-IR				Mid-IR		AO
Telescope	Image	Spec	IFU	MOS	Image	Spec	IFU	MOS	Image	Spec	AO
LBT	X	X		X	X	X		X	X	X	X
Keck 1	X	X		X	X	X	X	X			X
Keck 2	X	X		X	X	X					X
HET		X		X							
SALT	X	X		X							
Subaru	X	X		X	X	X		X	X	X	X
Gemini N	X	X	X	X	X	X	X	X			X
Gemini S	X	X	X	X	X	X		X			X
Magellan/Baade	X	X		X	X	X					
Magellan/Clay	X	X		X	X	X		X			X
MMT	X	X		X	X	X		X	X	X	X

NOTE: Acronyms are defined in Appendix C.

eral efforts to provide some coordination and integration to the OIR System. The McCray report, *A Strategy for Ground-Based Optical and Infrared Astronomy*[5] first recommended an NSF-funded program aimed at enlarging open access and simultaneously providing new resources for instrumentation at the non-federal telescopes. This approach was subsequently endorsed by AANM and ultimately implemented as TSIP. Over a period of 10 years, TSIP provided 453 new, open-access nights on large telescopes and helped to enable the construction of 13 new instruments for these telescopes.

Between 1996 and 2010, a group called ACCORD (the AURA [Association of Universities for Research in Astronomy] Coordinating Council of Observatory Research Directors) met periodically to discuss matters of common interest among the operators of medium- and large-aperture telescopes, including both federal and non-federal facilities.[6] This group operated without any specific authority outside of the control of the individual observatories. The goal of ACCORD was to develop consensus perspectives that could be presented to funding agencies and to policy-making and strategic planning committees. In addition, ACCORD supported some activities of broad benefit to the community, such as formulating an adaptive optics development roadmap.[7] Such community-wide planning is an important way to develop the U.S. OIR System.

See Section 6.3 for a discussion and recommendation about future system planning activities.

Impact of Resources through Diverse Usage

The combined resources represented by the U.S. OIR System are considerable. A justification for characterizing these facilities as a single system rather than a collection of individual telescopes with overlapping capabilities is the way that they are used to carry out scientific research. Unlike many academic pursuits where the primary resources are privately owned and reside in personal laboratories, libraries, or computers, the field of observational astronomy necessarily relies on shared resources in the form of multipurpose telescopes and data archives. The larger the number of researchers having access to these principal tools and their products, the more diverse are both the questions pursued and the science that is accomplished.

Furthermore, the vast majority of U.S. researchers depend on access to multiple facilities, whether open or proprietary. Ground-based data are often combined with

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[5] NRC, 1995, *A Strategy for Ground-Based Optical and Infrared Astronomy*, National Academy Press, Washington, D.C.

[6] ACCORD became defunct in 2010 following the release of NWNH and the transition to the current NSF AST director.

[7] "A Roadmap for the Development of United States Astronomical Adaptive Optics," 2008, http://www.aura-astronomy.org/news/AO_Roadmap2008_Final.pdf, accessed February 1, 2015.

space-based data, and many studies are conducted across a range of wavelengths, as noted in Chapter 2. Large projects are carried out by large teams, in which some of the participants bring access to private facilities to the collaboration. The NOAO Ground-Based OIR System Roadmap Committee Survey[8] conducted in 2011 states that 74 percent of the survey respondents were satisfied with the capabilities that they could currently access through these dynamic collaborative mechanisms. Note that this statement predates the decision by NSF to divest several of the federal telescope assets in the Northern Hemisphere as recommended by the PRC.[9]

This NOAO Roadmap Survey revealed that most U.S. researchers obtain and use the data they need from multiple available sources (see Figure 3.2; use of multiple telescopes by individuals is indicated by connecting lines and their emphasis). The most heavily used facilities (used by more than 20% of respondents), were, in order of usage, Keck 2 10-meter, SDSS 2.5-meter, Gemini North 8-meter, Keck 1 10-meter, NOAO/KPNO Mayall 4-meter, Gemini South 8-meter, MMT 6.5-meter, NOAO/CTIO Blanco 4-meter, and Magellan-Baade 6.5-meter.

The small, medium, and large telescopes listed in Table 3.1 account for more than 9,000 nights of telescope time yearly available to U.S. proposers and annually generate approximately 2,000 refereed publications (corrected by the U.S. fraction). The number of individual principal investigators (PIs) from U.S. institutions, summing the lists from these observatories, exceeds 1,500 per year. The number of people—scientific, technical, and administrative—employed to support the subset of these observatories that are primarily U.S. organizations is more than 700. Appendix B provides demographic data from observatories that responded to a request by the National Research Council for input on the numbers of employees in science, technical, and engineering positions; the numbers of proposals accepted; total users; and resulting publications.

Through broad participation of the professional astronomical community comes an increased chance for high-impact discovery. Survey data such as images, photometry, or limited spectroscopy from the Digitized Palomar Observatory Sky Survey (DPOSS), Two Micron All Sky Survey (2MASS), SDSS, and Wide-Field Infrared Survey Explorer (WISE) have been available to all researchers and lead to the high impact of these projects (Appendix B shows 600 papers per year based on SDSS data). Among PI-generated observations at pointed (as opposed to survey) telescopes, the productivity (papers published per telescope) and the impact of the

[8] NOAO, 2012, Ground-Based O/IR System Roadmap Committee Community Survey Summary of Results from U.S. Based/Sponsored Respondents, http://ast.noao.edu/sites/default/files/SummaryDocumentSystemRoadmapCommunitySurveyV1.5.pdf.

[9] National Science Foundation (NSF), 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

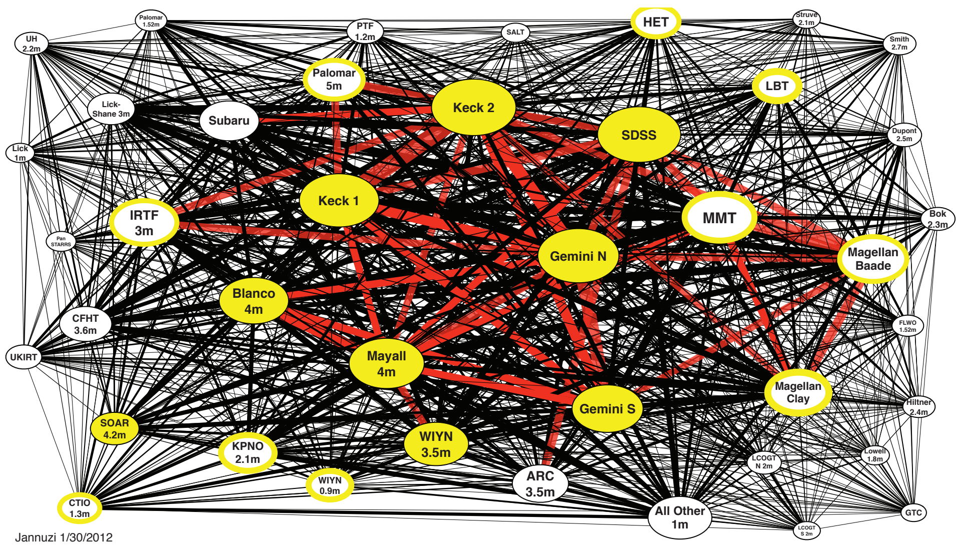

FIGURE 3.2 This figure, from the National Optical Astronomy Observatory Ground-Based Optical and Infrared (OIR) System Roadmap Committee report submitted to the Portfolio Review Committee, shows the relative number of common users of different telescopes through the thickness of the lines (red or black) connecting the facilities. The thicker the line, the more common users. For example, many researchers used both Gemini North and Keck 1 and 2 during the period covered by the survey (2008-2011). The relative number of U.S. users of each telescope in the U.S. OIR System from 2008 to 2011 is indicated by the size of the ellipse. The U.S. OIR community makes extensive use of all the U.S. OIR system facilities, independent of their access status, through scientific collaboration, time exchanges, and open-access programs. Facilities colored yellow received significant federal funding in support of either instrumentation or operations or other related activities of the facility. There were 1,178 respondents to the survey. Complete survey results are available at http://ast.noao.edu/about/committees/system-roadmap. SOURCE: Courtesy of B. Jannuzi (University of Arizona) and the National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation.

papers (defined as the ratio of the number of citations for a paper relative to the mean or median citation count among all papers that year) have been tracked for all the major (above 3.5 meters in size) OIR ground-based telescopes worldwide.[10] Considering data between 2008 and 2012, Keck, the Very Large Telescope (VLT), the United Kingdom Infrared Telescope (UKIRT), the Canada France Hawaii Telescope (CFHT), and Subaru are consistently at or near the top of the productivity

[10] D. Crabtree, 2014, A bibliometric analysis of observatory publications for the period 2008-2012, *Proceedings of the SPIE* 9149, Observatory Operations: Strategies, Processes, and Systems V, 91490A.

rankings, while HET, Keck, UKIRT, CFHT, and Magellan lead rankings in impact per paper. The total impact per telescope (defined as the average impact per paper times the number of papers from that telescope) is led by Keck, UKIRT, CFHT, VLT, and Subaru. For Keck, over a 3-year period about 75 percent of the time on the two 10-meter telescopes went to PIs at the university partners Caltech, University of California, and University of Hawaii, and the other 25 percent went to 238 programs with PIs at 57 different institutions; in 2012, 39 percent of the lead authors of Keck AO papers were from non-partner institutions, illustrating the diverse community associated with the high productivity and large impact of this facility.[11] Keck, CFHT, Magellan, and Gemini each have a large number of unique PIs per year (see Appendix B), while the lowest impact facilities had a factor of 10 fewer.

CONCLUSION: Interest from and telescope usage by a large, diverse, and active community of high-quality researchers is correlated with high-impact scientific output.

3.2 CURRENT DATA MANAGEMENT— ARCHIVES, SOFTWARE, AND DATA CENTERS

Archives are increasingly important in both space-based and ground-based astronomy for the long-term science return of facilities. There are now more papers published based on Hubble Space Telescope (HST) archival data than papers based on the original observations.[12] There are many archives in the United States associated with different observatories and long-term projects, with different levels of output. While space-based archives are a routine part of NASA missions, archives for ground-based data are not uniform.[13] Ground-based public archives are the most well developed for large surveys such as SDSS.[14] For the most part, OIR facilities with individual PI science programs have not provided public archives (with the exception of Gemini, Keck, and, more recently, NOAO). Chapter 5 of *New*

[11] See white paper by Cohen and Martin; note that as indicated in Table 1, public access to Keck is now reduced from 25 to 17% with the cancellation of TSIP. (J. Cohen and C. Martin, 2014, "The Crucial Role of W.M. Keck Observatory in the U.S. Astronomical System," white paper submitted to the committee).

[12] NASA, Hubble Space Telescope, 2011, "Hubble Racks up 10,000 Science Papers," December 6, http://www.nasa.gov/mission_pages/hubble/science/10k-papers.html.

[13] NSF, 2012, *Advancing Astronomy in the Coming Decade.*

[14] The SDSS project had approximately three times the publication rate of the most productive of the facilities mentioned above, the pair of Keck telescopes. SDSS led the citation rankings of all facilities in 2009 (J.P. Madrid and D. Macchetto, 2009, High-impact astronomical observatories, *Bulletin of the American Astronomical Society* 41:913-914).

Worlds, New Horizons in Astronomy and Astrophysics[15] (NWNH) included a section "Data and Software," subdivided into "Data Archives" and "Data Reduction and Analysis Software." The "Data Archives" section emphasized the high science return from the public archives for HST, SDSS, and 2MASS, and the high expected return from future large archives such as that for LSST. NWNH noted that the Virtual Observatory (VO) has established data archiving standards that should enhance the value of archival data sets. It also noted that NASA includes data handling and archiving as an integral component of its space missions. Here is a brief summary of representative current large archives from U.S. ground-based OIR facilities.

Examples of Current Ground-Based OIR Data Archives

2MASS

2MASS was the first digital, OIR all-sky survey from the ground, started in 1997 and completed in 2001 and conducted at near-IR *J, H, Ks* wavelengths. Its data products include a digital sky atlas with 4 million 8-arcminute x 16-arcminute fields, a point source catalog with positions and fluxes for 300 million stars and other unresolved sources, and an extended source catalog with positions and magnitudes for more than 1 million galaxies and nebulae. The data are publicly available through the Infrared Processing and Analysis Center (IPAC).

Gemini Observatory

All OIR raw data and metadata such as observing logs are publicly available after 12 months via the Canadian Astronomy Data Centre (CADC); no catalogs are published.

Keck Observatory

In collaboration with NASA, Keck makes OIR raw data from DEIMOS, ESI, HIRES, KI, LRIS, MOSFIRE, NIRC, NIRC2, NIRSPEC, and OSIRIS instruments publicly available after a default proprietary period of 18 months via the Keck Observatory Archive through the NASA Exoplanet Science Institute at IPAC. Pipelined "quick-look" data products are also available for some instruments. No catalogs are published.

[15] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

NOAO Science Archive

The NOAO Science Archive provides access to two types of data products. Relatively high-level data products (typically uniformly reduced, calibrated, re-projected, and stacked images but not catalogs) from most of the surveys carried out with NOAO facilities are available for public use. The larger fraction of the holdings includes all raw data taken by every NOAO instrument since 2004. Individual reduced images are included for the few instruments (wide-field imagers) with data reduction pipelines. Proprietary access is provided immediately to investigators with ongoing programs; public access is provided for all data after a default proprietary period of 18 months.

Sloan Digital Sky Survey

SDSS includes *ugriz* data and spectra. The last SDSS-III release, DR12,[16] includes over a billion catalogued objects and 5 million spectra from four surveys (BOSS [Baryon Oscillations], MARVELS [precision radial velocities], and SEGUE and APOGEE [galactic structure in the optical and *H*-band, respectively]). SDSS-IV is now under way. The raw data, the pipeline-reduced data, and science-ready catalogs are all made publicly available after a 12-month proprietary period through a web-enabled database hosted at Johns Hopkins University via a 5-year, but possibly renewable, grant.

PTF/iPTF

The fully automated private Palomar Transient Factory (PTF) and Intermediate Palomar Transient Factory (iPTF) optical *g*-band and *R*-band wide-field survey obtained with the Palomar Oschin 48-inch Schmidt telescope is archived at IPAC. There was a small public data release in the spring of 2014, with the rest of the PTF data to follow in 2015 and iPTF in 2016.

Las Cumbres Observatory Global Telescope

LCOGT provides optical image and source catalogs through an agreement with IPAC; currently 870,000 images and 2 billion photometric measurements are available. Data are proprietary for the initial 12 months.

European Projects

There are also a number of European-led survey projects whose data are world-public. These include UKIDSS (in *Y, J, H*, and *K* filters, currently with a catalog of 84 million objects measured in the Large Area Survey, 63 million in the Galactic

[16] S. Alam, F.D. Albareti, C.A. Prieto, F. Anders, S.F. Anderson, B.H. Andrews, E. Armengaud, É. Aubourg, S. Bailey, J.E. Bautista, R.L. Beaton, T.C. Beers, et al., 2015, The eleventh and twelfth data releases of the Sloan Digital Sky Survey: Final data from SDSS-III, arXiv:1501.00963 [astro-ph.IM].

Clusters Survey, and 700 million objects in the Galactic Plane Survey), iPHAS (*r, i,* and *H-alpha* data currently for 200 million galactic plane sources), and UVEX (*U, g, r* filter data, currently for 200 square degrees). There are six public infrared surveys from the VISTA 4-meter telescope that are also slowly becoming available to the U.S. community. VLT data become publicly accessible after a proprietary period.

The Virtual Observatory

The International Virtual Observatory Alliance (IVOA) has defined a number of standards and protocols to facilitate the interoperation of data centers and to permit the exploitation of heterogeneous, distributed collections of astronomical data; it is not a data repository in its own right. The U.S. Virtual Astronomical Observatory (USVAO; formerly the National Virtual Observatory) was a nationally funded project to use these technologies; however, USVAO has been terminated, and HEASARC, MAST, and IPAC have taken responsibility for maintaining its core functions. LSST has a baseline plan of using VOEvent to broadcast its alerts. An unfunded consortium of interested organizations has formed the USVAO to maintain a U.S. representation at the IVOA, and the American Astronomical Society Working Group on Astronomical Software is forming a VO special interest group for discussions and collaborations within the U.S. astronomical community on VO standards.

3.3 FUTURE DATA MANAGEMENT NEEDS

NWNH recommended that "Proposals for new major ground-based facilities and instruments with significant federal funding should be required as a matter of agency policy to include a plan and if necessary a budget for ensuring appropriate data acquisition, processing, archiving, and public access after a suitable proprietary period."[17] This is a worthy goal for all major surveys from both public and private facilities. Starting in 2011, NSF required applicants for funding to include a data management plan in their grant proposals.

A second issue raised in NWNH and reiterated by the PRC report[18] was long-term data curation, with the following recommendation: "NSF, NASA, and DOE should plan for effective long-term curation of, and access to, large astronomical data sets after completion of the missions or projects that produced these data, given the likely future scientific benefit of the data. NASA currently supports widely used curated data archives, and similar data curation models could be adopted by NSF and DOE."[19] While the archiving of data is a long-established part of the culture of astronomy, continuing to enhance the curation and accessibility of data is

[17] NRC, 2010, *New Worlds, New Horizons,* The National Academies Press, Washington, D.C., p. 31.
[18] NSF, 2012, *Advancing Astronomy in the Coming Decade.*
[19] NRC, 2010, *New Worlds, New Horizons,* p. 147.

consistent with new and pending federal mandates concerning access to the results of federally funded research. NSF released its public-access plan for availability of published papers in March 2015.[20]

CONCLUSION: Consistent with NWNH recommendations and federal mandates, a data archive that is publicly accessible and well curated is a commendable central goal for every major survey from a public or private facility.

Finally, NWNH noted that general-purpose community analysis software packages for data reduction and processing have aged and were not designed for the era of big data. There is thus a concomitant need for development of and investment in new, flexible, modular packages. New general-purpose software toolkits will be needed, especially when LSST comes online.[21] The adoption of standard VO interfaces and metadata by different archives would help facilitate searches and analyses involving multiple databases.[22]

These issues are important to address in the coming era of even larger databases.[23] Listed below are examples of some of the many planned archives, culminating in a discussion of the LSST archive.

Planned Data Archives

DECam (including DES and Open Use time)

There are two classes of data taken with the DECam on the CTIO Blanco 4-meter, both of which will ultimately end up in the NOAO science archive: DES data and community data resulting from NOAO time allocations. Raw and calibrated pixels in *g*, *r*, *i*, *z*, and *Y* filters are made available after a proprietary period for each (the proprietary period for DES images is 12 months). In addition, there are two planned releases of co-added, calibrated images and catalogs for the DES

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[20] NSF, 2015, *Public Access Plan: Today's Data, Tomorrow's Discoveries: Increasing Access to the Results of Research Funded by the National Science Foundation,* March 15, http://www.nsf.gov/pubs/2015/nsf15052/nsf15052.pdf.

[21] S. Oey, P. Price, L. Hartmann, J.U. Monnier, and C.U. Miller, 2014, "Enabling Science: OIR System Software Tools," white paper submitted to the committee.

[22] See the white paper by Drory et al. discussing integration of archiving practices (N. Drory, M. Shetrone, and N. Gaffney, 2014, "Software and the US OIR System," white paper submitted to the committee).

[23] See the following presentations to the committee on October 12, 2014, available at http://sites.nationalacademies.org/BPA/BPA_087934#presentations: David Silva, National Optical Astronomy Observatory, "NOAO Today and Tomorrow"; Richard White, Space Telescope Science Institute, "Data Panel Discussion"; George Helou, California Institute of Technology, "Archiving Ground-Based Data: Perspective from Space"; Mario Juric, Large Synoptic Survey Telescope.

data, one based on the first two observing seasons and the second following the full five seasons of data. It is expected that these will be archived and served in the short term by the National Center for Supercomputing Applications (NCSA), which leads DES Data Management. For the longer term, these DES data releases will be curated by NOAO.

Pan-STARRS

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) survey from the PS1 telescope in Hawaii has repeatedly imaged 75 percent of the observable Northern Hemisphere in *g, r, i, z, y* passbands since 2010. Its full catalog will be publicly released in April 2015[24] through an interface at the MAST. The current PS1 database includes 35 billion measurements for 6.5 billion objects.

Zwicky Transient Facility

The Zwicky Transient Facility (ZTF), the follow-up to PTF and iPTF, will produce synoptic 976 megapixel images in *R*-band and *g*-band obtained with the Palomar Oschin 48-inch Schmidt telescope. Raw and calibrated pixels will be archived. Photometry will be cataloged for all objects seen in the frames. IPAC at Caltech will process and host the data, with an interface through the Infrared Science Archive (IRSA). Thanks to NSF Mid-Scale Innovations Program (MSIP) funding, approximately half of the ZTF data are expected to be public, starting in 2018, with staged data releases thereafter. Transient alerts will be broadcast publicly in near-real time beginning in the third year of operation.

LSST

The LSST archive, to be housed at the NCSA for user access, will accumulate approximately 20 TB of *ugrizy* data per night, generating for the archive 60 PB of raw data and 15 PB of catalog data over the 10-year lifetime.[25,26] Level 1 data[27] and

[24] See K. Chambers, 2015, "Pan-STARRS and the Future of Optical/IR Sky Surveys in the Northern Hemisphere," white paper submitted to the committee.

[25] PB = petabyte = 10^{15} byte = 1 million billion bytes = 1 million gigabytes; TB = terabyte = 10^{12} bytes = 1 thousand gigabytes.

[26] Large Synoptic Survey Telescope, "LSST Data Management," http://www.lsst.org/lsst/science/concept_data, accessed March 2, 2015.

[27] In the context of LSST, the term Level 1 is used to mean the following: Nightly processing resulting in catalogs of objects whose positions or fluxes have changed, resulting in alerts broadcast worldwide after 60 seconds. This includes solving for orbits of solar system objects (Large Synoptic Survey Telescope, 2013, "LSST Data Products Definition Document," http://ls.st/dpdd).

Level 2 data[28] are project deliverables. Data products will include calibrated and co-added images, per-epoch object catalogs, and static-sky object catalogs. These catalogs will contain stellar and galaxy photometry, positions (and parallaxes and proper motions for stars), and shapes measured with enough fidelity to be used to measure cosmic shear. LSST will generate alerts for transients that will be made public within 1 minute, along with enough information for the recipients to act on the alert. Although LSST will not provide a sophisticated alert broker (see Section 5.2), the system is expected to provide information to help external brokers classify alerts (e.g., *ugrizy* postage stamps and the complete light-curve of any object detected at that position). Once a year (twice in the first year) there is expected to be a release of all the raw and processed data and the transient and static-sky catalogs. There will be approximately a 1-year delay from the time that the last data are taken until the release. This data release will be made available to everyone in the United States and Chile and to LSST's international partners. The release will be in the form of a sophisticated database, although the project will also support access using traditional formats. The LSST project will generate well-calibrated databases that can be used for a broad range of science without further data processing.

CONCLUSION: LSST will accumulate more than 20 TB of data per night during an anticipated 10-year lifetime. The LSST project will generate sophisticated, well-calibrated databases that will enable many projects without further data processing. Generating higher-level data and algorithms is not part of the LSST project charge.

LSST will provide a data center to serve alerts, images, and catalogs. In addition, 10 percent of the center's resources (CPU cycles and database storage) will be available to the community to support additional activities, such as computing and saving additional parameters for a subset of brighter galaxies. Additionally, the LSST data center at NCSA will be colocated with publicly available petascale computing facilities, and it should be possible to apply for time to carry out extensive analyses that require more than the 10 percent of its resources that LSST will make available.[29] This will be important for the community, since downloading

[28] Level 2: Yearly processing of all the data taken to date, including de-blending sources and optimal processing of multi-epoch data, resulting in calibrated catalogs of positions, fluxes, and shapes for objects of sufficient quality to enable a wide range of science without returning to the pixels. The Level 2 catalogs will include characterization of object variability (parallaxes, proper motions, summaries of Lomb-Scargle periodograms) as well as flux measurements optimized for various purposes (aperture, psf, Petrosian, model), and structural parameters for simple galaxy models (e.g., 2-component constrained Sersic indices) and some derived quantities such as photo-z catalogs.

[29] This need for computer center access is particularly crucial for researchers at smaller institutions (C.T. Liu, B. Willman, J. Pepper, M. Rutkowski, D. Norman, K. Cruz, J. Bochanski, H. Lee, J. Isler, J. Gizis, J.A. Smith, et al., 2014, "Maximizing LSST's Scientific Return: Ensuring Participation from Smaller Institutions," white paper submitted to the committee).

large data sets to local computing resources is not practical. Generating higher-level algorithms and data products for science beyond the primary mission is not part of the LSST project's scope. These Level 3 data[30] activities are important for extracting the maximum science from NSF's large investment in this forefront instrument; DOE is already funding efforts to prepare for Level 3 processing aimed at its scientific goals.

CONCLUSION: LSST will provide a data center to serve alerts, images, and catalogs, with 10 percent of the center's resources (CPU cycles and database storage) reserved for the community. The data center will be colocated with publicly available petascale computing facilities at NCSA.

With 10 million time domain events per night, orbits for 6 million solar system bodies, 3 billion galaxies, and over 10 billion stars, the LSST archive will be a treasure trove for research. For many astronomers, analyzing these data will be a new mode of doing science. The astronomical community needs to develop algorithms and procedures for data processing and analysis for specific scientific programs. Useful activities to build this competence include developing training networks (see Section 3.4 for discussion and a recommendation in this regard), establishing data challenges, and applying LSST algorithms to existing and forthcoming large data sets such as DES, PS1, and PTF/ZTF. This practical work will help to standardize data protocols,[31] equip the community to use LSST data, and produce substantial scientific results.

CONCLUSION: LSST will use standard protocols to serve data where available (e.g., VOEvent) and will work with the community to evolve and establish future standards.

CONCLUSION: Making effective use of petabyte-scale databases ("big data") requires new skills, and the astronomical community working in this area needs to continue to develop algorithms and procedures for data processing and analysis to take advantage of the next generation of data sets.

CONCLUSION: The scientific return from large surveys (both ground- and space-based) would be maximized if their data and catalogs were made

[30] Level 3: Further processing of the Level 1 or 2 catalogs or the pixels, enabling more specialized studies. For example, GALFIT-style modeling of bright galaxies, generating catalogs of interacting galaxies, or co-processing LSST images with near-IR data.

[31] From the LSST page: "The content of the alert packet itself will be formatted to confirm to VOEvent (or other relevant) standard. Where the existing standard is inadequate for LSST needs, LSST will propose extensions and work with the community to reach a common solution" (Large Synoptic Survey Telescope, 2013, "LSST Data Products Definition Document," http://ls.st/dpdd).

widely available using standard protocols, with appropriate data products made available for copying or downloading when possible. Because of the volumes of data involved, the centers serving the data would be most useful if appropriate public computing cycles and storage were available to users to take data-intensive analysis to the data instead of requiring redundant copies of the data on local computing resources.

3.4 TRAINING IN OBSERVING, INSTRUMENTATION, AND SOFTWARE

Training in instrumentation, software, observing, and data analysis is an essential aspect of the astronomical enterprise.[32] Classroom training in basic instrumentation and data acquisition and analysis is often part of the undergraduate curriculum for astronomy and physics majors. More specialized training occurs both at the undergraduate and graduate levels within research groups, either at universities or national laboratories such as NOAO and the NASA centers, or as part of an NSF Research Experiences for Undergraduates (REU) program. Many students may not know where their true interests and talents lie without trying several different kinds of projects, thus broadening their experience and skill sets. As a result, advanced technical training may be somewhat haphazard and often occurs toward the end of the student experience. As astronomical instrumentation and software grow increasingly complex, there is a greater need for specialization in these fields and with it, a need for earlier and more systematic training.

Training in Instrumentation

Many graduate programs look favorably upon applicants with expressed interests in instrumentation. There are currently 40 departments in 38 institutions in the United States offering a Ph.D. in astronomy, astrophysics, or planetary sciences.[33] Of these, half have instrumentation programs in OIR; radio, millimeter,

[32] Training has been discussed in several of the recent reports that consider the OIR System: NSF, 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges,* report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee, August 12, http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf; NOAO, 2009, *Final Report of the Committee on Access to Large Telescopes for Astronomical Instruction and Research (ALTAIR),* https://www.noao.edu/system/altair/files/ALTAIR_Report_Final.pdf; NOAO, 2007, *Renewing Small Telescopes for Astronomical Research,* https://www.noao.edu/system/restar/files/ReSTAR_final_14jan08.pdf; NRC, 1995, *A Strategy for Ground-Based Optical and Infrared Astronomy,* National Academy Press, Washington, D.C.

[33] S. Nicholson and P.J. Mulvey, 2014, Roster of the Physics Departments with Enrollment and Degree Data, 2013, *Focus On*, August, American Institute of Physics Statistical Research Center, http://www.aip.org/statistics/reports/roster-physics-2013.

and submillimeter (RMS); or spaceflight instrumentation (including rocket-borne instruments). Several departments create a holistic training experience for their students by engaging them in instrument testing and technology development, observing, and analysis,[34] and have used observatory access to train future instrument builders.[35] Smaller telescopes play an important role in providing testbeds for instrumentation and training for instrument builders, somewhat analogous to that of university-scale experiments within NASA's suborbital program. By way of example, the Texas Robotic Optical Transient Search Experiment telescope and the Palomar 60-inch have been used effectively as testbeds for robotic operation.

The NSF Portfolio Review Committee warned that "it will be difficult to attract and retain the next generation of instrument builders."[36] and NWNH noted "the opportunities for training students in instrumentation have declined precipitously over the past 20 years. Training for the next generation of instrumentalists is most efficient when there is a steady-state hierarchy of project sizes, so that people can progress from relatively smaller, simpler, and faster projects to responsibilities in larger and more complex activities."[37] As the complexity and the timescale for developing instruments for major telescopes grows, it is increasingly difficult to find projects that are sufficiently self-contained yet also offer substantial opportunities to develop students' and postdocs' skills. The beginning of new instrument projects does not always dovetail or overlap with the completion of old ones, so appropriate projects are not always available for students.

There are a number of actions that could help nurture and train young instrumentalists. These include offering training networks (see the end of this section for a recommendation in this regard), maintaining small instrument programs for undergraduate departments to develop talent for graduate programs, running instrumentation workshops and NSF REU programs concentrating on instrumentation, and fostering diverse populations in instrument groups.[38]

Training in Software

Astronomical software involving observations falls into two broad categories: that needed to run the hardware and take raw data, and that needed to render raw data astronomically useful. The former category requires not only software

[34] S.E. Tuttle, H. Lee, C. Froning, and M. Montgomery, 2014, "Builders Instead of Consumers: Training Astronomers in Instrumentation and Observation," white paper submitted to the committee.

[35] J. Cohen and C. Martin, 2014, "The Crucial Role of W.M. Keck Observatory in the U.S. Astronomical System," white paper submitted to the committee.

[36] NSF, 2012, *Advancing Astronomy in the Coming Decade*, p. 71.

[37] NRC, 2010, *New Worlds, New Horizons,* p. 149.

[38] See white paper by Nota et al., submitted to the Astro2010 State of the Profession Infrastructure Study Group on Demographics, http://sites.nationalacademies.org/BPA/BPA_049492.

engineering expertise, but also adequate understanding of the hardware and the ability to interface with the instrument builders. The latter category characterizes and removes (in most cases) instrumental signatures and proceeds to produce tables of astronomical quantities—calibrated spectra, fluxes, positions, and for extended objects, model parameters and shapes; this is often referred to as pipeline processing. Pipeline processing requires a sophisticated understanding of the characteristics of the raw data, the scientific problems that it can be used to elucidate, and the trade-offs involved in algorithmic and implementation choices. There is a third category of software that takes pipeline products and produces quantities of interest for one or another specific astronomical study, sometimes involving outputs from multiple pipelines.

There are unsolved problems at all stages in the processing. Most of the algorithmic innovation in these pipelines comes from people trained as astronomers. Building a successful production pipeline requires software engineering as well as astronomical expertise, and pipelines are typically masterminded by astronomers who have chosen to specialize in algorithms, often working within software groups or large collaborations.

Learning the art of astronomical software often occurs within the context of research. Students involved in instrumentation projects often participate in the design and development of control and acquisition software as well as hardware. Because pipeline expertise is not widespread in the astronomical community, and because the complexity of modern algorithms and codes is not widely appreciated, many students are self-taught, and many never acquire more than the rudiments of software engineering. Therefore, a more systematic approach to algorithm training could be valuable.

Training in Observation

Large surveys such as 2MASS, SDSS, and Gaia (and eventually LSST) provide products of great value to astronomers, but surveys are not the whole story in astronomy. As practitioners in the field—at all levels—are becoming less connected to raw data acquisition and more reliant on data products available in archives, the need for training in observational techniques and associated data uncertainties is less obvious but remains important. Such training will assure not only appropriate use and acquisition of data today, but also help in the design of next-generation instruments and facilities.

Small OIR telescopes, equipped with basic instrumentation, are available on many campuses.[39] Learning observing techniques on these is adequate for pro-

[39] The telescope maker DFM, for example, has sold over 100 telescopes with apertures 0.4-1.0 meter to colleges and other organizations and individuals (per DFM Engineering, Inc.).

grams such as basic imaging or spectroscopy, which benefit from the proliferation of well-designed hardware and software systems, including efficient observing scripts, data reduction pipelines, and open-access analysis suites.

The most demanding observational programs still require the presence of the observer making real-time observations with the telescope. Even the most detailed specifications planned in advance of an observing run account only partially for the variations in observing conditions and instrument state that are typical of ground-based observing. Students therefore have much to learn from active participation in real-time decision making and data acquisition at the telescope for tasks such as the alignment of multi-slit masks and coronagraphs, altering priorities on a target list in response to quick-look analysis of incoming data, deciding after a first observation whether an object warrants a larger investment of telescope time, or changing programs entirely based on seeing or weather conditions.

Many premier research telescopes are accessible to Ph.D. students through competitive proposals. Some students also have privileged access via their institutional affiliations. Despite this, student access to the largest telescopes, equipped with more complex instrumentation requiring more sophisticated experimental design, is often limited. This limitation is in part because such telescopes are heavily oversubscribed and also because they are logistically more complicated to use. Insofar as students are increasingly removed from instrument operation and data acquisition, they are at increasing risk of failing to appreciate the shortcomings of the data with which they may work and less well positioned to write persuasive and effective proposals for telescope time.

Cross-Institutional Training in Critical Areas

Coursework and on-the-job apprenticeships offered by individual institutions are sometimes supplemented by cross-institutional workshops and "summer schools" (which are not necessarily held in the summer). These are particularly well suited to more advanced training for which teaching resources may not be available, either because of small enrollments or limited expertise. Radio astronomers have long used such workshops and schools to teach aperture synthesis techniques. European countries have integrated these methods into their astronomical culture via long-term multi-institutional collaborations (known as training networks) involving graduate students, postdocs, and faculty members intended to provide methodological instruction through research; examples in astronomy include networks aimed at preparing for weak lensing[40] and Gaia[41] data. An important feature

[40] Dark Universe through Extragalactic Lensing, http://www.roe.ac.uk/ifa/DUEL/, accessed February 1, 2015.

[41] Gaia Research for European Astronomy Training, http://great.ast.cam.ac.uk/great-itn/, accessed February 1, 2015.

of these networks is that their activities are spread out over the course of 2 or more years, giving a cohort time to develop and solidify.

The U.S. OIR community has made relatively little use of training networks, although there are some well-established annual series (e.g., the adaptive optics workshops at Santa Cruz,[42] the astroinformatics and astrostatistics workshops run by Penn State and others,[43] the Santa Barbara Modules for Experiments in Stellar Astrophysics (MESA) workshops,[44] NASA's Sagan Exoplanet Summer Workshops,)[45] and recently, LSST community workshops;[46] however, none aim to train a generation of students in the science and technology of emerging fields. NOAO has sponsored many workshops for the community.[47] All of these workshops are specialized one-time meetings that do not develop a cohort of experts the way training networks can.

The small numbers of builders of astronomical instruments and writers of astronomical software make these segments of the OIR ecosystem particularly vulnerable to major changes in the astronomical landscape. There is concern that the current downturn in funding is squeezing out a future generation of instrument builders. The writers of astronomical software face a potential embarrassment of riches, with the prospect of more data available than people able to render it useful to the astronomical community. It is essential to provide adequate training in order to fully exploit future data sets. One solution to help train future generations would be a connected sequence of schools specifically aimed at training students in, for example, the data reduction and analysis skills relevant to LSST[48] and, more generally, big data science. As astronomy moves to more research based on

[42] Center for Adaptive Optics, 2013, "14th Annual International Summer School," http://cfao.ucolick.org/aosummer/.

[43] See submitted comments by Borne (K. Borne, "Comments on Data Science Methods," white paper submitted to the committee). The white paper by Loredo et al. from the LSST Informatics and Statistics Science Collaboration emphasizes the need to have broader educational efforts in addition to summer schools and the creation of interdisciplinary funding programs; the coauthors are a mix of astronomers and information scientists (T.J. Loredo, J. Babu, K.D. Borne, E. Feigelson, P. Freeman, J. Hilbe, Z. Ivezic, C. Schafer, and A. Siemiginowska, 2014, "Astronomical Information Sciences for O/IR Synoptic Survey Astronomy," white paper submitted to the committee).

[44] "Modules for Experiments in Stellar Astrophysics," http://mesa.sourceforge.net/, accessed February 1, 2015.

[45] NASA, NASA Exoplanet Science Institute, "Sagan Exoplanet Summer Workshop," http://nexsci.caltech.edu/workshop/, accessed February 1, 2015.

[46] Large Synoptic Survey Telescope, "LSST Project and Community Workshop," https://project.lsst.org/meetings/lsst2014/, accessed March 1, 2015; Large Synoptic Survey Telescope, "LSST and NOAO Observing Cadences Workshop," https://project.lsst.org/meetings/ocw/, accessed March 1, 2015.

[47] NOAO, "National Optical Astronomy Observatory Affiliated Meetings," http://ast.noao.edu/activities/meetings-colloquia/noao, accessed February 1, 2015.

[48] L. Walkowicz, A. Connolly, Z. Ivezic, M. Juric, V. Kalogera, C. Lintott, P. Marshall, and M. Strauss, 2014, "Software Training Networks in the LSST Era," white paper submitted to the committee.

pipeline-reduced data sets, it becomes even more important that the consumers understand the processing algorithms in order to understand the strengths and limitations of the catalogs. Some aspects of Level 3 LSST processing (e.g., transient alert brokers) could be structured as training networks competed by NSF, with student and postdoc development as one of the deliverables.[49] Such schools might likewise be appropriate for advanced topics in instrumentation, software visualization tools, and analysis.[50]

CONCLUSION: Specialized training in general observing, instrumentation, software, and data analysis techniques is essential for ensuring that the next generation of astronomers has the requisite skills to accomplish the best science.

RECOMMENDATION: The National Science Foundation (NSF) should support a coordinated suite of schools, workshops, and training networks run by experts to train the future generation of astronomers and maintain instrumentation, software, and data analysis expertise. Some of this training might best be planned as a sequence, with later topics building on earlier ones. NSF should use existing instrument and research programs to support training to build instruments.

3.5 MAINTAINING INSTRUMENTATION AND SOFTWARE EXPERTISE

Behind every great observational scientific breakthrough there is an instrument builder. Without new tools for discovery, the ability to push the frontiers in astronomy would be significantly compromised. Increasingly, scientific instruments require an enormous investment in software to exploit the data; LSST, like the Large Hadron Collider (LHC), is as much a software project as a hardware project. It is imperative to sustain talent in these important areas in order for the U.S. astronomical community to remain competitive.

Beyond graduate study, the career paths for instrument builders and software specialists are less well-defined than for theorists and observers. In order to be

[49] See also the white paper by Willman et al. on training and Level 3 efforts (B. Willman, K. Olsen, J. Bochanski, N. Brandt, A. Burgasser, W. Clarkson, M. Cooper, K. Covey, H. Ferguson, E. Gawiser, M. Geha, et al., 2014, "Enabling a Diverse User Community to Produce Cutting-Edge Science with LSST," white paper submitted to the committee).

[50] See white papers submitted to the committee by Liu et al. on training (C.T. Liu, B. Willman, J. Pepper, M. Rutkowski, D. Norman, K. Cruz, J. Bochanski, H. Lee, J. Isler, J. Gizis, J.A. Smith, et al., 2014, "Maximizing LSST's Scientific Return: Ensuring Participation from Smaller Institutions") and by Drory et al. specifically on software training (N. Drory, M. Shetrone, and N. Gaffney, 2014, "Software and the US OIR System."

professionally competitive, students in these fields essentially complete two theses: one instrumental or software-oriented and one focusing on the analysis, or what some would consider "the science." Many institutions make sure that instrumentation students have independent ownership of their projects and publish their results in journals specifically for instrumentation. However, the lengthy timeline for big instrument projects often leads to fewer publications for instrumentalists. This puts them at a disadvantage for prize postdocs and tenure advancement. The development timescale for big projects is much longer than a student or postdoc career, and it is more difficult for them to play central roles because groups cannot accept risk of failure or slips in schedule. These difficulties disincentivize potential instrument builders. Similarly, the increased importance of software to the astronomical enterprise, and the creativity and astronomical knowledge involved, is not always reflected in postdoctoral and faculty appointments.

CONCLUSION: Long timescales for complex projects and oversubscription of instrument funding lines discourage early career specialization in instrumentation.

It is worth noting that while there may be fewer academic tenure-track jobs for instrument builders and software experts, these graduates rarely have trouble finding employment outside of astronomy because they have outstanding technical training. While producing highly skilled individuals who leave astronomy adds high-level workers to society, that is not the primary motivation for training students in astronomy graduate programs. There is a perception inside and outside the United States that other countries are doing a better job at providing stable funding for engineers and instrumentalists. There are widespread views in the instrumentation community that many talented young instrument builders in the United States are following jobs to other countries. Because scientific productivity rests upon the success of instruments that are used at telescopes, the U.S. OIR community cannot risk losing this talent and expertise and ceding leadership to other countries.

A well-known challenge for instrumentation is that it is expensive to maintain a laboratory infrastructure that includes machine shops; project managers; and optical, mechanical, electrical, and software engineers. Often, laboratory personnel can be sustained only when universities make this a priority by allocating long-term funding; in many cases universities are either closing down labs or scaling back personnel. In addition, the community is increasingly at risk of losing small and medium telescopes (private and public) that provide testbeds for instrumentation.

There are also new challenges that are directly related to the increasing cost, size, and complexity of new instruments for 6- to 10-meter telescopes and the next generation of giant telescopes. The cost of observatory instruments now constitutes a significant fraction of the cost of the telescope. Seed money, typically needed to make a project competitive for funding through the Major Research Instrumentation (MRI) program, has become increasingly scarce. The Advanced Technologies and Instrumentation (ATI) and MRI programs are oversubscribed by greater than 5:1, and their budget lines are inadequate to support the rising costs of instruments. The MSIP program is a new line of support but is underfunded relative to the number of excellent proposals,[51] both on high-priority science recommended in decadal surveys and on new avenues of exploration. There is often a lead time of several years to obtain funding for instruments, which then take several years to complete and commission along with the writing of pipeline software.

CONCLUSION: NSF ATI and MRI funding is inadequate to support the rising cost of small and medium instrument projects.

Some financial support for instrumentation projects has emerged from federal agencies outside NSF, such as DOE and NASA. Over the past 30 years, the DOE National Laboratories have become increasingly engaged in ground-based OIR projects, which provide an avenue for both instrumentalists and software experts. Major projects under way or about to be undertaken include DECam by Fermilab in concert with NOAO, the LSST camera by Stanford Linear Accelerator Center (SLAC) in concert with NSF, and DESI by Lawrence Berkeley National Laboratory (LBNL) in concert with NOAO. The principal contributions of the DOE laboratories and their associated university scientists have been in instrument development and construction and to a lesser extent data processing. The teams at the national laboratories are program-oriented and can be expected to move on to non-astronomical projects when each program is completed. Some individuals, both from the labs and from the universities, may choose to continue pursuing astronomy, bringing their expertise with them.

Because instrument development on private facilities is more driven by PIs than by agency or national programmatics, there is still an important role for universities and small labs to play, especially with respect to training for later involvement in the larger-scale projects. NSF can have a significant impact through its research grants and instrumentation programs. Review panels recognize ideas that are creative. Many good ideas do percolate up through the grants program. However, it is more difficult to identify funding sources to explore the high-risk

[51] A presentation by Jim Ulvestad to the AAAC in November 2014 notes that there were 38 preproposals requesting $398 million; 12 full proposals were invited, and 2 full awards and 1 development award were funded, with about $14 million in annual funding for FY2014 and FY2015 (http://www.nsf.gov/attachments/130395/public/Ulvestad_NSF-AST-AAAC-2014Nov17.pdf); see also the NSF Mathematical and Physical Sciences Directorate's response to NWNH recommendations: NSF, 2014, *NSF Division of Astronomical Sciences (AST) Report*, http://www.nsf.gov/attachments/130395/public/Ulvestad_NSF-AST-AAAC-2014Nov17.pdf; NSF, 2015, "Dear Colleague Letter: Status of MPS/AST Response to Recommendations of New Worlds, New Horizons Decadal Survey," March 4, http://www.nsf.gov/pubs/2015/nsf15044/nsf15044.pdf.

but potentially transformative technologies that are needed for the United States to remain competitive.[52]

CONCLUSION: There is inadequate funding for instrumentation programs. This is largely the result of the increasing cost and complexity of instruments for the next generation of telescopes, with funding gaps between projects. The increased complexity of instruments also requires stronger engineering and project management components than in the past, and it is rare to have this as part of the training in astronomy instrumentation programs.

CONCLUSION: The need to complete complex expensive projects means that less funding is going toward explorative technology development.

See the previous Section 3.4 for a recommendation on support of instrument training, and Section 4.2 for a recommendation on investment in technology development.

[52] See the white papers submitted to the committee highlighting the need for instrument development and training as well as funding for transformational instrumentation and technologies: T.E. Armandroff, 2014, "Input from McDonald Observatory to the Committee on a Strategy to Optimize the U.S. OIR System in the Era of the LSST for Questions 3 and 10" and J.D. Monnier, J.T. Armstrong, M.J. Creech-Eakman, S.T. Ridgway, T.A. ten Brummelaar, and G.T. van Belle, 2014, "Funding Technology Development and Novel Instrumentation Today in Order to Enable Breakthrough Observing Techniques Tomorrow."

4

Pursuing the Science in the LSST and GSMT Era

4.1 SCIENCE-DRIVEN NEEDS FOR OIR INSTRUMENT CAPABILITIES

Transformative studies in key science areas, from planets and exoplanets, to stellar and galaxy evolution, to dark energy large-scale cosmology, will require specialized instrumentation and technology development as well as substantial increases in collecting area and/or field of view. *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH), the Portfolio Review Committee (PRC) report,[2] and *Vision and Voyages for Planetary Science in the Decade 2013-2022*[3] (VVPS) provide extensive discussions of critical high-priority questions and the instrumentation needed to answer them. This section summarizes some of the key capabilities that will be needed in the coming years to address different areas of research as the Large Synoptic Survey Telescope (LSST) and the Giant Segmented Mirror Telescopes (GSMTs) come online.

Wide-field, moderate-resolution, highly multiplexed spectrographs were highlighted in NWNH as synergistic instruments for LSST and Wide-Field Infrared Sur-

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[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., p. 79.

[2] National Science Foundation (NSF), 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

[3] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press, Washington, D.C.

vey Telescope (WFIRST) measurements of cosmic acceleration, and in the NWNH report of the Panel on Optical and Infrared Astronomy from the Ground[4] as versatile instruments on 4- to 8-meter telescopes for a large range of science drivers in four of the five science frontier panels (Cosmology and Fundamental Physics, Galactic Neighborhood, Galaxies Across Cosmic Time, and Stars and Stellar Evolution). In 2011, the National Optical Astronomical Observatory (NOAO) hosted a community workshop to explore in detail the science that could be achieved with BigBOSS,[5] now known as DESI,[6] which is a wide-field (3-degree-diameter) massively multiplexed (up to 5,000 targets per field) fiber-fed spectrograph. There are a number of other highly multiplexed spectrographs in development for 4- to 8-meter-class telescopes, which are not public access or are non-U.S., as detailed in Section 5.1. Such spectrographs and related integral field unit (IFU) systems will allow surveys of millions of galaxies at redshifts $z > 1$. These measurements will be crucial cosmological probes that provide insight into dark energy and the distribution of dark matter as well as study galaxy evolution and primordial star formation. These spectrographs are also critical for surveying large samples of Milky Way stars to understand the chemical evolution of the galaxy as well as nearby galaxies by providing precise elemental abundances. They will enable studies of the kinematics and dynamical evolution of the Milky Way and nearby galaxies. Gaia results will motivate further science cases. Community access to such a spectrograph would open up more possibilities for key high-impact science.[7] Further discussion and a recommendation for a wide-field, massively multiplexed spectrograph in the Southern Hemisphere is given in Section 5.1.

High-throughput, moderate resolution optical and near-IR spectrographs and spectropolarimeters on large and giant telescopes will be critical for a variety of observations, including transients (see discussion of LSST follow-up in Section 5.1 and a recommendation in Section 5.2), quasars, planetary atmospheres, individual objects such as stars, binaries, and galaxies measured in statistical samples, and individual objects studied as part of multi-wavelength campaigns.

High-contrast imaging and spectroscopy on large and GSMT-class telescopes will be necessary to map the structure and evolution of protoplanetary disks.

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[4] NRC, 2011, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., p. 353.

[5] National Optical Astronomy Observatory (NOAO), "Highly Mutiplexed Spectroscopy with BigBOSS on the Mayall Telescope: An NOAO Community Workshop," http://www.noao.edu/meetings/bigboss/, accessed February 1, 2015.

[6] Acronyms, especially those denoting individual instruments and missions, are defined in Appendix C.

[7] G. Rudnick, A. Myers, C. Badenes, T. Beers, S. Brittain, J. Carlin, D. Cinabro, M. Cooper, A. Connolly, E. Ellingson, X. Fan, et al., 2014, "The Need for Community Access to Highly Multiplexed Spectroscopy: DESI Availability in the Age of LSST," white paper submitted to the committee.

These capabilities will also provide details of the surfaces, atmospheres, and rings of solar system planets as well as small bodies in the solar system. The advent of giant telescopes along with adaptive optics (AO) coronagraphy offers the tantalizing prospect of direct imaging of Jupiter analogs around nearby solar-type stars. Large-aperture OIR telescopes help constrain parameters involved in most stellar processes, such as the formation and evolution of stars, characterizing the initial mass function, the effect of stellar duplicity, the influence of magnetic fields, mass loss, rotation, and the phenomena of supernova and gamma ray bursts. Further gains will be achieved through high-sensitivity, high-resolution imaging, spectroscopy, and spectropolarimetry on AO-equipped 6-meter and larger telescopes that can probe intrinsically fainter, more distant, and more varied targets. Studies of the structure of high-redshift galaxies with near-infrared (IR) AO instruments on large telescopes will complement ALMA observations of their gas content to provide insight on galaxy evolution and star formation processes. See Section 4.2 for more discussion and a recommendation on AO technology development.

The next generation of telescopes will extend observations to more crowded environments and much greater distances than current facilities. The light-gathering power of a 30-meter-class telescope at low-background, near-IR wavelengths is such that an AO-assisted spectroscopic performance at moderate resolution will significantly exceed that of the James Webb Space Telescope (JWST), in particular for compact sources, while an AO-fed IFU spectrograph will reveal galaxy structures, kinematics, and metallicities. High-resolution multi-object spectroscopy on large telescopes will further research in the field of galactic archaeology to probe the chemical composition of disk, bulge, and halo stars[8] and to survey star-forming molecular clouds in the Milky Way Galaxy to address the factors governing the initial mass function and the rates and efficiencies of star formation.[9] These spectroscopic capabilities enable studies of the topology, ionization state, and chemical enrichment of the intergalactic medium and the first galaxies at the end of the cosmic dark ages. As a result, near-IR spectroscopy on an AO-assisted 30-meter-class telescope will provide a detailed story of the properties and influence of the first stars and black holes on the intergalactic medium.

On galaxy scales, basic questions center on feedback mechanisms that affect star formation, energy transport in the interstellar medium, and metal enrichment, as well as the relationship between star formation history, supermassive black hole growth, and dark matter halos. These interrelations will help in understanding the formation and evolution of galaxies. Such studies are enabled at both low and high redshift by spectroscopic observations of rest-frame near-ultraviolet and optical

[8] M. Rich, 2014, white paper submitted to the committee.

[9] S.T. Megeath, 2014, "O/IR Capabilities and the Study of Star Formation in the Nearest 2 kpc," white paper submitted to the committee.

interstellar lines, dynamical measurements, high-angular-resolution imaging, and OIR photometry.

Polarimetry across a broad spectral range is important for characterizing magnetic fields to understand their role in active galactic nuclei (AGN), protostellar disks, cosmic ray propagation, energy transport in star-forming regions, and large-scale polarized dust emission that affects cosmic microwave background radiation.[10] In addition, development of OIR interferometry techniques would advance the understanding of exozodiacal and protoplanetary disks and the effect of magnetic fields on stars.[11] Extreme precision Doppler spectroscopy for radial velocity measurements by special-purpose instruments will be critical to exoplanet studies; see Section 4.2 for further discussion and a recommendation in this regard.

OIR astronomy will also remain critically important in the quest to determine cosmological initial conditions over the widest possible dynamic range, through observations of large-scale structure (using galaxies, intergalactic gas, and gravitational lensing) and of standard candles (primarily Type Ia supernovae). Large, ground-based optical imaging surveys such as LSST (described further in Section 4.4) will provide high signal-to-noise data for billions of galaxies.

Some pivotal instruments for future science are already in operation, such as wide-field optical and IR multi-object spectrographs and imagers; high-dispersion spectrographs; and AO systems on Gemini, LBT, MMT, Magellan, HET, and Keck. First generation instruments planned for TMT and GMT will include many of these decadal priority instruments, except for high-contrast optical and mid-IR AO imagers[12] and wide-field multiplexed spectrographs. These capabilities, combined with the significant increase in collecting area, will undoubtedly result in unprecedented and unimagined new scientific advances. Public access to large telescopes with these critical instrument capabilities (some of which already exist, such as high-resolution echelle optical spectrographs) is and will continue to be important to the community.[13]

CONCLUSION: Because of the diversity of critical astronomical studies in NWNH and VVPS, a variety of instruments, some already available, on large and medium telescopes will be integral to successful progress in

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[10] B.-G. Andersson, A. Adamson, K.S. Bjorkman, J.E. Chiar, D.P. Clemens, D.C. Hines, J.L. Hoffman, T.J. Jones, A. Lazarian, C. Packham, J.E. Vaillancourt, et al., 2014, "The Need for General-Use Polarimeters in the Era of LSST," white paper submitted to the committee.

[11] J.T. Armstrong, M.J. Creech-Eakman, J.D. Monnier, S.T. Ridgway, T.A. ten Brummelaar, and G.T. van Belle, 2014, "Supporting Community Access to Optical/Infrared Interferometry," white paper submitted to the committee.

[12] Section 4.3; R.A. Bernstein, G. Jacoby, P. McCarthy, et al., 2014, "Instrumentation and Technical Excellence in Astronomy in the LSST and ELT Era," white paper submitted to the committee.

[13] I.U. Roederer, 2014, white paper submitted to the committee.

understanding the universe in the next decade. These include a wide-field highly multiplexed moderate-resolution optical/near-IR spectrograph, a high-throughput, moderate-resolution spectrograph, a high-resolution IFU optical or infrared spectrograph, optical and near-IR imaging with adaptive optics, and extreme precision Doppler spectroscopy and AO coronagraphy.

In addition to large and extremely large telescopes, small (≤ 3-meter) and medium (3.5- to 5-meter) telescopes will continue to play an important role in many areas of science,[14] even if most are at non-federal observatories. Gaia and TESS are two satellites that will generate significant follow-up opportunities. LSST's catalog will include millions of objects near its bright end limits that are still accessible with small-aperture telescopes for imaging with a different cadence than LSST, and spectroscopy, spectropolarimetry, deeper observations, narrow-band imaging, or near-IR imaging, which are not possible with LSST. Such targets include, for example, T Tauri variable stars, novae and supernovae, AGNs that vary on timescales of hours, emission lines from planetary nebulae, star-forming regions, and starburst galaxies.

CONCLUSION: Small- and medium-aperture telescopes are useful for a range of science endeavors that require spectroscopy, spectropolarimetry, narrowband imaging, or a different cadence than LSST.

The PRC report,[15] NWNH,[16] and VVPS[17] assessed the OIR instrument needs of the community based on the science priorities and related key questions. Table 4.1 summarizes many critical capabilities needed in the coming years and some of the science that will be enabled by them. The list is not in priority order; some entries have recommendations in subsequent sections.

4.2 TECHNOLOGY DEVELOPMENT

Technology development continues to drive observational progress in OIR astronomy. Robust investment in technology development is essential to ensure that astronomical advances continue and that future breakthrough instruments are developed, as emphasized in the NWNH OIR panel report, VVPS, and in previous

[14] See the white papers submitted to the committee: S. Heathcote, 2014, "Cerro Tololo Inter-American Observatory in the LSST Era"; J.M. Strader, E.F. Brown, L. Chomiuk, E.D. Loh, and S.E. Zepf, 2014, "A View of Astronomy at Universities in the LSST Era."

[15] NSF, 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

[16] NRC, 2011, *Panel Reports—New Worlds, New Horizons,* Table 7.1.

[17] NRC, 2011, *Vision and Voyages for Planetary Science,* Table 10.1.

TABLE 4.1 Key Instrument Needs in the Era of the Large Synoptic Survey Telescope (LSST)

Instrument	Examples of Applications
Wide-field, highly multiplexed-moderate-resolution spectroscopy on 4- to 10-meter telescopes	Studies of individual interesting objects, compact stellar remnants, galaxy assembly fossil record, cosmic structure formation, first stars, cosmic acceleration, redshift distributions, Milky Way chemical and dynamic evolution
High-throughput, moderate-resolution, single-object spectrograph (and spectropolarimeter) on 6- to 30-meter telescopes	Transients (LSST follow-up), quasars, planetary atmospheres, individual objects (solar system objects, stars, binaries, galaxies)
Multi-conjugate AO on 6- to 30-meter telescopes	Circumstellar disks and protoplanetary, supernova progenitors, galaxy assembly, cosmic structures, black holes, first stars, planetary systems
Integral field unit optical, near-IR spectroscopy with adaptive optics (AO)	Protoplanetary disks, stars, high-redshift galaxies
High-resolution optical, near-IR imaging with AO	Solar system objects, planetary atmospheres, protoplanetary disks, stars, high-redshift galaxies
AO coronagraphy	Exoplanets, protoplanetary disks
Extreme precision radial velocity (Doppler) spectroscopy	Exoplanet detection
Small- and medium-aperture (1- to 5-meter) telescopes with low-resolution spectrographs and spectropolarimeters, and broadband and narrowband imaging from U band to 5 microns. Global arrays best; need rapid response.	Bright transients, nearby galaxies, stars, solar system objects

sections of this report.[18] Several key areas for continued technology development highlighted in NWNH were adaptive optics (also in VVPS), precision radial velocities, and astronomical detectors. There is a widespread sense that the United States has fallen behind other countries in technology development and that innovation, while not stalled, is eroding.

AO has now become a foundational technology on most large ground-based telescopes (e.g., the Keck, Gemini, MMT, Magellan), enabling diffraction-limited, near-IR imaging and spectroscopy that rivals and even surpasses that from space (see Figure 4.1). No longer thought of as follow-up technology to be implemented merely as an add-on, AO is now integrated into modern telescope system and instrumentation design from the beginning.

[18] See also the following AO presentations to the committee on October 12, 2014: Claire Max, University of California Observatories/UC Santa Cruz, "The Status of AO Worldwide"; Phil Hinz, University of Arizona, "The Role of Adaptive Optics—with Examples"; and Richard Dekany, California Institute of Technology (available at http://sites.nationalacademies.org/BPA/BPA_087934#presentations).

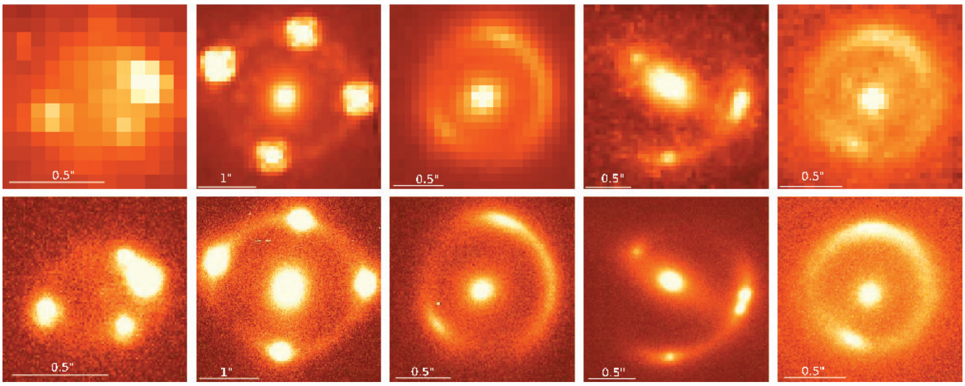

FIGURE 4.1 *Top row:* Images of five gravitational lens systems obtained with Hubble Space Telescope (HST)/Near Infrared Camera and Multi-Object Spectrometer (NICMOS) in the *H* band. The object in the center of each image is the foreground lensing galaxy. The background galaxy is lensed into arcs or a ring, and sometimes has multiple images of its central active galactic nuclei. *Bottom row:* Keck adaptive optics (AO) images of the same systems obtained with Near Infrared Camera 2 in the *Kp* band. The AO images are noticeably sharper than the HST images. SOURCE: Courtesy of Professor Chris Fassnacht (University of California, Davis).

AO techniques traditionally have been best suited for detailed study of individual objects, achieving the highest spatial resolution for resolved objects, crowded fields, and high contrast, and for obtaining the greatest sensitivity for spectroscopy on large apertures. Maturation of technologies developed over the past 20 years, and continuing today, shows emerging capability for other applications, which in the future may even include wide-field imaging and highly multiplexed resolved-object spectroscopy. To achieve the current precision of AO, key developments have been made in the production of stable lasers, large-format deformable mirrors, and lower-noise wavefront sensors. Adaptive Secondary Mirrors (ASM) have dramatically changed the scope and power of AO in the past few years. An ASM can allow any telescope a wide field of view (FOV) at 0.2-0.3 arcsecond resolution in the near-IR (1-3 microns),[19] and coupling an ASM with the sensitive wavefront sensor

[19] See, for example, the GLAO prototype at the MMT (M. Hart, N.M. Milton, C. Baranec, K. Powell, T. Stalcup, D. McCarthy, C. Kulesa, and E. Bendek, 2010, A ground-layer adaptive optics system with multiple laser guide stars, *Nature* 466(7307):727-729).

at the Magellan Telescope has enabled the first visible wavelength AO science.[20] An ASM is being deployed on the Very Large Telescope (VLT) and designed for several of the next generation of giant telescopes.

Going forward, many aspects of NWNH and VVPS science need robust AO capabilities across wavelengths, spectral resolution, and cadence.[21] The growing science impact of AO today is the result of previous investments, which peaked in the mid-2000s under the Adaptive Optics Development Program (AODP) at just short of $20 million per year but have now fallen to less than one-fifth of that.[22] Optimized usage of current and next-generation large apertures relies on continuing investment channels for this high-payoff (albeit expensive) area of technology development. The AO required for the next-generation large-aperture telescopes is a significant extension of today's state-of-the-art technology.[23] At the same time, clever application of AO techniques to smaller apertures[24] can create unique roles for these facilities also operating at their full spatial resolution and sensitivity.

Dedicated exoplanet-detecting instruments, from high-contrast AO coronagraphs on ground-based telescopes to IR Doppler spectrographs for high-precision radial-velocity measurements, will be crucial to provide characterization of these systems. Combining these observations with synoptic studies and space-based observations will elucidate how planetary systems form and whether systems like the solar system are common or rare. Specifically in the field of precision radial velocity for exoplanet detection, the Europeans have been investing in new technology for the past decade; the United States is not keeping up.

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[20] L.M. Close, J.R. Males, K. Morzinski, D. Kopon, K. Follette, T.J. Rodigas, P. Hinz, Y.-L. Wu, A. Puglisi, S. Esposito, A. Riccardi, et al., 2013, Diffraction-limited visible light images of orion trapezium cluster with the Magellan adaptive secondary adaptive optics system (MagAO), *The Astrophysical Journal* 774(2):94.

[21] NRC, 2011, *Panel Reports—New Worlds, New Horizons,* Table 7.3.

[22] Association of Universities for Research in Astronomy, Coordinating Council of Observatory Research Directors, 2008, *A Roadmap for the Development of United States Astronomical Adaptive Optics*, http://www.aura-astronomy.org/news/AO_Roadmap2008_Final.pdf.

[23] See white paper by Monnier highlighting the need for more AO development (J.D. Monnier, J.T. Armstrong, M.J. Creech-Eakman, S.T. Ridgway, T.A. ten Brummelaar, and G.T. van Belle, 2014, "Funding Technology Development and Novel Instrumentation Today in Order to Enable Breakthrough Observing Techniques Tomorrow," white paper submitted to the committee) and the presentations to the committee on October 12, 2014, by Claire Max and by Phil Hinz (Claire Max, University of California Observatories/UC Santa Cruz, "The Status of AO Worldwide"; Phil Hinz, University of Arizona, "The Role of Adaptive Optics—with Examples" (both available at http://sites.nationalacademies.org/BPA/BPA_087934#presentations).

[24] For example, Robo-AO does large-scale surveys robotically at the Palomar 60″. It has been used for exoplanet confirmations of Kepler candidates as well as observations of massive storms on Uranus (University of Hawaii, Institute for Astronomy, "Robo-AO: Autonomous Laser-Adaptive-Optics for Few Meter Class Telescopes," http://www.ifa.hawaii.edu/Robo-AO/, accessed February 1, 2015).

In the newly formed NN-EXPLORE (NASA-NSF Exoplanet Observational Research) partnership to support precision radial velocities,[25] the National Science Foundation (NSF) will provide facility support on the 3.5-meter WIYN telescope and NASA will provide funding to build an Extreme Precision Doppler Spectrometer (EPDS). This partnership was designed to meet the recommendations of NWNH that "NASA and NSF should support an aggressive program of ground-based, high-precision, radial-velocity surveys of nearby stars in order to validate and characterize exoplanet candidates."[26] This partnership should prove to be a valuable addition for the community, and the committee applauds the willingness of NSF and NASA to coordinate activities in a way that responds to long-standing community input and maximizes productivity and ground-based OIR community access.[27]

NASA's announcement of intent for the instrument sets a requirement of 50 cm/s precision and a goal of 10 cm/s. Before Earth-like masses can be reliably detected, nightly stellar noise of the order of 100 cm/s in the most stable stars[28] must be overcome and 10 cm/s precision must become the state of the art rather than merely a goal. A deliberate development program improving wavelength calibration and detector technology is needed, in parallel with analytic efforts to overcome stellar noise.[29]

Detector technology has evolved over the past 20 years, with larger sizes and greater sensitivities over larger wavelength ranges. Wide-field imaging and massively multiplexed spectrographs are possible because of the development of detectors with mosaics of hundreds of millions of pixels, as highlighted in NWNH. The community relies on a small number of experts to build and tune charge-coupled device controllers. In the infrared, the number of vendors with high-quality, low-noise, 1-5 micron detectors has declined considerably. Since astronomy is generally a photon-starved science, the development of superconducting single-photon broadband detectors would help to advance heterodyne detection and resolution of narrow astronomical lines, fringes in interferometry, and wavefront sensing

[25] L. Allen and D. Silva, 2014, "KPNO in the Next Decade and Beyond," white paper submitted to the committee.

[26] NRC, 2010, *New Worlds, New Horizons,* p. 20.

[27] Although agreed on by the agencies and announced as this committee was deliberating, the proposed radial velocity instrument is an example of a partnership that in the future can be held to the standard described in Chapter 6, with an eye toward building instrumentation that optimizes the entire U.S. System.

[28] F. Pepe, C. Lovis, D. Ségransan, W. Benz, F. Bouchy, X. Dumusque, M. Mayor, D. Queloz, N.C. Santos, and S. Udry, 2011, The HARPS search for Earth-like planets in the habitable zone, *Astronomy and Astrophysics* 534(A58):1-16.

[29] For a planned workshop in this regard, see "The Second Workshop: Extreme Precision Radial Velocities" (http://exoplanets.astro.yale.edu/workshop/EPRV/Home.html, accessed February 1, 2015).

for adaptive optics. MKID (microwave kinetic inductance detectors), detectors made with superconducting material that would allow very precise measurements of the frequency of incoming photons, are beginning to be incorporated in OIR instruments.[30]

In addition to the technology endeavors highlighted above, future technological development in, for example, optical interferometry, next-generation detectors, astro-photonics, lightweight mirrors, and fiber positioners will be key to achieving decadal science. Determining these technical priorities would be a logical part of the community's system strategic planning process (see Section 6.3), with implementation supported by funding streams within NSF (MSIP, ATI, and MRI as appropriate) and NASA and Department of Energy (DOE) technology programs.

Pushing the frontiers requires supporting a range of innovative projects from ALMA and LSST to small grants for basic exploratory research. The existing ATI program in principle supports the small, simpler, and faster programs to advance technology and to train the next generation of instrument builders. As stated in NWNH, while the technology itself is important, it is vital that sufficient support for the development and strengthening of the technology workforce be part of these technology efforts as well (see Section 3.5). A desirable by-product of investment in technology development is the creation of more robust opportunities to train the next generation of instrumentalists. If NSF does not maintain strong support for the infrastructure needed for innovation, basic science, and training of the next generation, the United States will fail to lead in the technology development that is critical for scientific discovery.

CONCLUSION: Science realized today relies on the investments made in the past, both on specific telescope and instrument development and more general technology development. Going forward, a similar mix of near-term and intermediate-term efforts is required in order to maintain healthy progress in astronomy.

RECOMMENDATION: The National Science Foundation (NSF) should continue to invest in the development of critical instrument technologies, including detectors, adaptive/active optics, and precision radial velocity measurements. NSF should also use existing instrument and research programs to support small-scale exploratory programs that have the potential to develop transformative technologies.

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[30] See, for example, the Array Camera for Optical to Near-IR Spectrophotometry (ARCONS) instrument (B.A. Mazin, S.R. Meeker, M.J. Strader, P. Szypryt, D. Marsden, J.C. van Eyken, G.E. Duggan, A.B. Walter, G. Ulbricht, and M. Johnson, 2013, ARCONS: A 2024 pixel optical through near-IR cryogenic imaging spectrophotometer, *Publications of the Astronomical Society of the Pacific* 125(933):1348-1361).

4.3 IMPORTANCE OF THE GIANT SEGMENTED MIRROR TELESCOPES

GSMTs are being developed privately by two consortia based in the United States: TMT at Maunakea, expected to have first light in 2024, and the 24.5-meter GMT at Carnegie's Las Campanas Observatory in Chile, expected to have first light in 2021 (both shown in Figure 4.2). The advent of these two GSMTs, along with European Southern Observatory's 39-meter European Extremely Large Telescope (E-ELT), will revolutionize OIR astronomy by achieving angular resolution and depth far beyond current telescopes. The GSMTs will contribute critically to addressing the majority of the next decade's principal science questions[31] and are required for five key science programs in NWNH, including the direct detection of giant exoplanets and the precise characterization of the Milky Way's central black hole, environments and progenitors of supernovae and gamma ray bursts (GRBs), dark matter halos, and physical properties of the first stars.[32] VVPS highlights GSMTs for future solar system observations such as thermal emission from Neptune and compositional measurements of trans-Neptunian objects.

The most progress will come from combined studies at many different wavelengths using both ground-based and space-based facilities, as mentioned in Chapter 2. This essential synergy was clearly demonstrated by the combination of HST and the Blanco 4-meter, Gemini 8-meter, and Keck 10-meter telescopes for many significant discoveries, most notably the accelerating universe. Similarly, the TMT and GMT will be critical complements to major new facilities, including LSST, ALMA, JWST, Gaia, WFIRST, and Euclid.

The TMT and GMT will provide these synergistic capabilities through advanced adaptive optics and powerful first-light science instruments, including optical and near-infrared high-resolution spectrographs, moderate-resolution multi-object spectrographs, and imagers. In addition, since sensitivity increases in proportion to the fourth power of diameter for diffraction-limited point sources, a 30-meter telescope will be over 80 times more sensitive than a 10-meter telescope for some projects. Moderately large fields of view will facilitate, among other efforts, the deployment of multi-object spectrographs that will be critical to many areas of science (see Sections 4.1 and 5.1).

NSF and the TMT Observatory Corporation signed a cooperative agreement in 2013 initiating a 5-year planning study to examine potential models for NSF participation in TMT for the benefit of the U.S. astronomical community. NOAO is leading TMT participation planning activities under the cooperative agreement, engaging the U.S. astronomical community, and it has established a U.S. TMT Liaison office and a U.S. TMT Science Working Group. This planning effort will

[31] NRC, 2011, *Panel Reports—New Worlds, New Horizons,* Table 7.1.
[32] NRC, 2011, *Panel Reports—New Worlds, New Horizons,* Table 7.2.

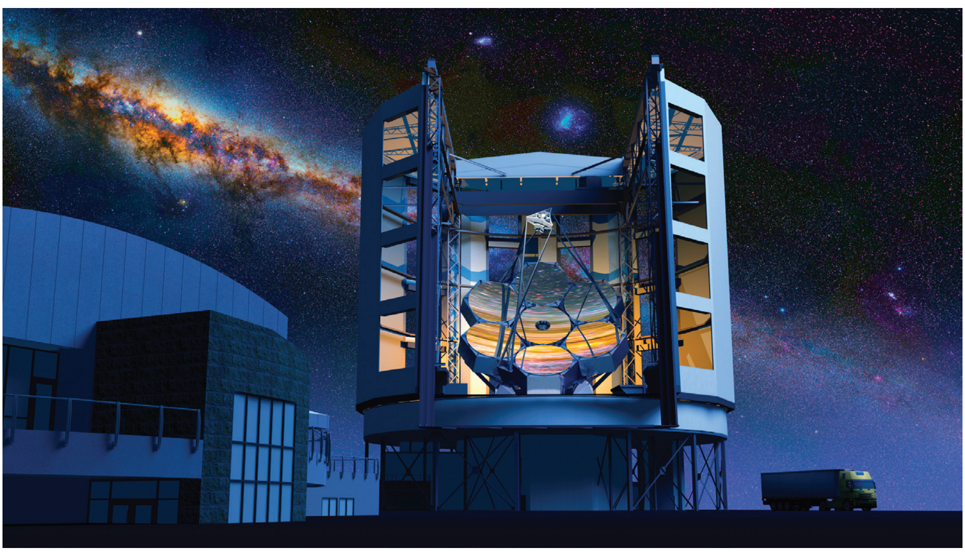

FIGURE 4.2 Conceptual sketches of the Thirty Meter Telescope (*top*) and Giant Magellan Telescope (*bottom*). SOURCE: (*Top*) Courtesy of TMT International Observatory; (*bottom*) Courtesy of Giant Magellan Telescope, GMTO Corporation.

lead to a set of reports based on input solicited from the scientific community that will constitute a plan with options for possible U.S. participation in TMT. The TMT Science Working Group notes several ways in which the scientific return from federal investment in TMT might be maximized, including public access to archived data, public participation in key science programs, and contributions by university groups to second-generation instruments. When the TMT International Observatory (TIO) was legally incorporated, AURA became an associate in TIO and delegated NOAO to execute AURA's associate member responsibilities on behalf of the U.S. astronomical community.

The GMT partners[33] have indicated a willingness to entertain new partners and have extended membership on their Scientific Advisory Committee to members of the U.S. astronomical community who are not associated with partner institutions. The Giant Magellan Telescope Organization Board[34] and the GMT Science Advisory Committee[35] are open to a variety of mechanisms for community participation in return for federal support, including open peer-reviewed access, open community participation in Key Projects, and partnering with NSF and non-member institutions to develop second-generation instrumentation and AO technology.[36]

NWNH recommended that "due to severe budget limitations, a federal partnership in a GSMT will be limited to a minority role in one project"[37] and recommended a 25 percent share in a GSMT as a goal, either through Major Research Equipment and Facilities Construction (MREFC) funds or operations costs, as a formal partner. VVPS endorsed the NWNH recommendations and support for the GSMTs. As of the writing of this report, the two GSMT projects (GMT and TMT) appear to be moving toward construction. Even though the current funding situation does not allow substantial involvement in the GSMT projects by NSF beyond the 5-year agreement with TMT, the committee underscores the importance of

[33] The GMT consortium includes participation by Carnegie Observatories, the University of Texas at Austin, Texas A&M, the University of Arizona, the University of Chicago, Harvard University, and the Smithsonian Astrophysical Observatory. International partners include Australia, Korea, and Brazil.

[34] W.L. Freedman, E. Moses, C. Alcock, T. Armandroff, M. Colless, W. Couch, D. DePoy, R. Franzen, L. Hicke, B. Jannuzi, R. Kirshner, R. Kolb, et al., 2014, "Community Access to the GMT in the Era of LSST," white paper submitted to the committee.

[35] R.G. Kron, E. Berger, R. Blum, H.W. Chen, A. Cochran, J. Crane, G. Da Costa, J. Dalcanton, M. Donahue, J. Eisner, D. Fabricant, J.-J. Lee, et al., 2014, "The Role of GMT in the OIR System in the LSST Era," white paper submitted to the committee.

[36] See Patrick McCarthy, Giant Magellan Telescope, "GMT and the OIR System in the Era of the LSST," presentation to the committee on October 12, 2014, http://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_090096.pdf.

[37] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics,* p. 231.

community involvement in the future.[38] There are a number of ways that this could occur at a federal participation level at or below that recommended in NWNH. It would be prudent for NSF to plan to enable broader access by preparing for the possibility of engagement with either or both of the projects—for example, through shared operations costs, instrument development, exchange partnerships (see Chapter 6), or partnership in science projects. These options could be pursued in the event that NSF receives more funding, or by trading off other facilities and programs.

CONCLUSION: With their monumental gains in sensitivity and angular resolution, the GSMTs are poised to revolutionize the understanding of key astrophysical phenomena as well as to open new, unexpected frontiers. They are likely to be underfunded once they become operational.

CONCLUSION: The GSMTs will be crucial for detailed follow-up investigations of many discoveries from existing and planned facilities, including ALMA, Gaia, LSST, JWST, Euclid, and WFIRST, and will make major contributions to many of the next decade's key science questions, including the nature of debris disks, the physics of planet formation, the growth of black holes, and the advent of the first galaxies.

RECOMMENDATION: The National Science Foundation should plan for an investment in one or both Giant Segmented Mirror Telescopes in order to capitalize on these observatories' exceptional scientific capabilities for the broader astronomical community in the Large Synoptic Survey Telescope era—for example, through shared operations costs, instrument development, or limited partnerships in telescope or data access or science projects.

4.4 THE LARGE SYNOPTIC SURVEY TELESCOPE

LSST is the top-ranked large ground-based project in NWNH, and also highly ranked in VVPS. It will be an 8.4-meter telescope designed for wide-field imaging, with a 9.6 square degree FOV (see Figure 4.3). It is being built through a public-private partnership, with federal support from NSF and DOE and broad private

[38] The U.S. TMT Science Working Group surveyed U.S. astronomers about TMT priorities. Of the 467 respondents, 68% favored a partnership share in TMT of at least 15% for the U.S. community beyond the current partners (M. Dickinson, 2015, Recent developments with the Thirty Meter Telescope, *NOAO Newsletter*, March 2015, https://www.noao.edu/noao/noaonews/mar15/pdf/111syssci.pdf).

FIGURE 4.3 Conceptual sketch of the Large Synoptic Survey Telescope. SOURCE: Courtesy of Large Synoptic Survey Telescope Corp.

and international support.[39] It has entered the NSF MREFC funding line for construction, the M1M3 mirror is nearing completion, and the camera team has just

[39] Institutional members are Adler Planetarium, Argonne National Laboratory, Brookhaven National Laboratory (BNL), California Institute of Technology, Carnegie Mellon University, Chile, Columbia University, Cornell University, Drexel University, Fermi National Accelerator Laboratory, George Mason University, Google, Inc., Harvard-Smithsonian Center for Astrophysics, Institut de Physique Nucleaire et de Physique des Particules (IN2P3), Johns Hopkins University, Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)-Stanford University, Las Cumbres Observatory Global Telescope Network, Inc., Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), National Optical Astronomy Observatory (founding member), Northwestern University, Princeton University, Purdue University, Research Corporation for Science Advancement (founding member), Rutgers University, SLAC National Accelerator Laboratory, Space Telescope Science Institute, Texas A & M University, The Institute of Physics of the Academy of Sciences of the Czech Republic (affiliate), Pennsylvania State University, University of Arizona (founding member), University of California, Davis, University of Illinois, Urbana-Champaign, University of Michigan, University of Oxford, University of Pennsylvania, University of Pittsburgh, University of Washington (founding member), Vanderbilt University, and Fisk University.

successfully completed a DOE Critical Decision (CD-2) Review. LSST will survey the southern sky over 20,000 square degrees in six ultraviolet and optical through near-IR bands (0.3-1.1 microns) to a final depth of $r = 27.5$ mag, visiting each field about 1,000 times during its planned 10-year project lifetime.

The design of LSST makes it useful for a wide range of astronomical studies. LSST will detect about 10 billion stars in the Milky Way and nearby galaxies that will provide information about the structure of galaxy disk and halo components. Transient events such as supernovae, optical counterparts of GRBs, AGNs, periodic variable stars, Kuiper Belt objects, and near-Earth asteroids will be probed in the time domain. Statistical studies of galaxies will be aided by observations of about 3 billion galaxies, the distributions of which will be used to understand dark matter on large scales through gravitational lensing, and the data will allow studies of dark energy through supernovae, weak gravitational lensing, clusters of galaxies, and baryon acoustic oscillations. A wide range of key science questions in the decadal priority lists will be impacted when LSST comes online.

LSST science requirements were defined by considering the needs of four broad areas: dark energy, solar system, optical transients, and galactic structure. The fact that the *LSST Science Book*[40] is more than 500 pages long, detailing science programs from the solar system to stellar populations, the Milky Way, nearby galaxies, transients, distant galaxies, AGNs, supernovae, lensing, dark matter, and large scale structure, underscores the critical role of LSST in enabling the astronomical community to tackle a wide variety of astronomical questions when it comes online. Its massive public archive will stimulate worldwide investigations. Although a key project is the dark energy part of the survey, which is a self-contained project with Level 3 support from DOE through the Dark Energy Survey Collaboration (DESC), there is no doubt that the cadenced observations of billions of stars and galaxies as well as solar system objects will drive enhanced science benefits from follow-up observations using complementary facilities.

[40] Large Synoptic Survey Telescope Corp., 2009, *Large Synoptic Survey Telescope Science Book Version 2.0.* November, http://www.lsst.org/lsst/science/scibook.

5

Realizing the Full Science Potential of LSST

The path from Large Synoptic Survey Telescope (LSST) data to science results is not simple. The scope of the LSST survey, the volume and rate of the data, will require additional capabilities for the community to maximize the science from LSST. While a great amount of research can be pursued with LSST data alone, the availability of other instrumentation, specific precursor studies,[1] and development of new software systems will result in a huge increase in the quantity and quality of science results from LSST. This section describes instrumentation, software, and coordination needs that will enhance the returns from LSST data.

5.1 FOLLOW-UP TELESCOPE AND INSTRUMENTATION NEEDS

LSST will carry out extremely powerful deep, fast, and wide multi-band photometric surveys in the Southern Hemisphere. The requirements for follow-up observations, both photometric and spectroscopic, will span a range of timescales and telescope sizes. While significant capability could be contributed by existing small- and medium-aperture telescopes, the depth of a single LSST observation suggests that the majority of follow-up observations of all types will require large telescopes. An optimized spectroscopic system would exploit and enhance all three

[1] See white paper discussion by Willman et al. on the need for precursor Level 3 data products and tool development (B. Willman, K. Olsen, J. Bochanski, N. Brandt, A. Burgasser, W. Clarkson, M. Cooper, K. Covey, H. Ferguson, E. Gawiser, M. Geha, et al., 2014, "Enabling a Diverse User Community to Produce Cutting-Edge Science with LSST," white paper submitted to the committee).

of LSST's capabilities. Individual very faint sources will be followed up by 6- to 30-meter-class telescopes, pushing the frontiers at high redshift and in the local universe down the luminosity function. A high-throughput, moderate-resolution spectrograph on Gemini South or on another large southern telescope accessible to the community would help satisfy the spectroscopic needs. Optical transients, depending on the timescale and flux requirements, can be followed by small-aperture robotic arrays and by medium-aperture telescopes through target-of-opportunity (ToO) observations or dedicated programs, addressing decadal survey priorities in time-domain astronomy. LSST will produce only two-dimensional maps of the cosmos (providing precise measurements of fluxes, colors, and shapes); this gives rise to the need for wide survey follow-up. The Sloan Digital Sky Survey (SDSS) is by some measures the most highly cited astronomical facility of the past decade, with some 6,250 papers cited about 275,000 times, for an h-index of 205.[2] SDSS enabled a rich array of astronomical discoveries through its combination of photometric (two-dimensional, 2D) and spectroscopic (three-dimensional, 3D) surveys. LSST promises much more.

The science reach of LSST could be substantially enhanced by developing for the U.S. astronomy community a very-wide-field, massively multiplexed, spectroscopic capability. This facility should be capable of overlapping the majority of the sky area covered by the LSST surveys.[3] Such a wide-field instrument or instruments should be sufficiently multiplexed to enable spectroscopic surveys of tens of millions of objects over several years. The science case for such a capability is rich for objects of a wide range of brightnesses, as already indicated in Section 4.1.

A primary systematic error for extragalactic and cosmological studies with LSST will be uncertainty in photometric redshift estimates (based on colors and fluxes).[4] Deep, wide redshift surveys that substantially overlap LSST are needed to both train and calibrate photometric redshift estimates. The sample sizes here are much smaller than those needed for the measurements of spatial clustering (hundreds of thousands versus tens of millions), but they have much more stringent requirements for sample completeness in order to mitigate systematic errors and therefore will likely need to include larger-aperture facilities.

Worldwide, the currently planned, highly multiplexed (N roughly 500 or larger) spectroscopy facilities include DESI on the KPNO 4-meter, HETDEX on the HET, WEAVE on the William Herschel Telescope (WHT), EMIR on the GTC,

[2] Recovered from ADS in February 2015 (Smithsonian Astrophysical Observatory/NASA Astrophysics Data System (ADS), Query Results from the Astronomy Database, http://tinyurl.com/42jxy).

[3] The time spent within different regions of the LSST footprint on the sky is still under discussion and should be chosen with a view to increasing its scientific value. Conversely, future space missions like WFIRST may find it valuable to choose survey fields that overlap with LSST.

[4] A. Abate, J.A. Newman, and S.J. Schmidt, 2014, "Spectroscopic Needs for Training of LSST Photometric Redshifts," white paper submitted to the committee.

Prime Focus Spectrograph[5] (PFS) on Subaru, the Maunakea Spectroscopic Explorer (MSE) to replace CFHT,[6] and LAMOST (China) in the Northern Hemisphere, with 4MOST on VISTA, MOONS at the VLT, and, if it proves possible to correct its wide field, GMACS on the GMT in the Southern Hemisphere.[7] Except for DESI, these are all on private telescopes or at non-U.S. facilities to which U.S. astronomers do not have access. There is a lack of wide-field, multiplexed spectroscopic capability in the Southern Hemisphere to which the U.S. community has ready (public) access. This deficiency will negatively impact the ability to achieve maximum science from LSST.

CONCLUSION: There is currently no wide-field, highly multiplexed spectroscopic capability on medium- or large-aperture telescopes in the Southern Hemisphere in the U.S. Optical and Infrared (OIR) System.

CONCLUSION: Wide-field, highly multiplexed spectroscopic capabilities on medium- and large-aperture telescopes in the Southern Hemisphere in the LSST era would be of great benefit to the U.S. OIR System, enabling a wide variety of science including follow-up spectroscopy of LSST targets.

RECOMMENDATION: The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way.

For cosmological studies, massive, sufficiently deep and broad redshift surveys of galaxies and quasars enable measurement of the baryon acoustic oscillation feature in the spatial two-point correlation function and of the redshift-space anisotropy of clustering due to redshift-space distortions. The former provides a geometrical probe of the cosmic expansion history, and the latter constrains the growth rate of large-scale structure over cosmic time. Together these techniques provide constraints on dark energy, neutrino masses, and modified gravity. In recent years, it has been recognized that the constraints on dark energy can be tremendously enhanced by the synergy between these two 3D clustering measure-

[5] H. Murayama, R. Ellis, T. Heckman, M. Seiffert, and D. Spergel, 2014, "Prime Focus Spectrograph on Subaru to Follow Up LSST Targets," white paper submitted to the committee.

[6] A.W. McConnachie, J. Bullock, P. Garnavich, P. Guhathakurta, G. Hasinger, M. Mateo, M. Strauss, and B. Tully, 2014, "The Maunakea Spectroscopic Explorer (MSE) Status Update," white paper submitted to the committee.

[7] Acronyms, especially those denoting individual instruments and missions, are defined in Appendix C.

ments, and the complementary 2D weak-lensing measurements that will come from LSST. That synergy is enhanced by maximizing the sky overlap of the 3D and 2D samples and by having the galaxies responsible for the 2D lensing well sampled in the spectroscopic survey. DESI on the KPNO 4-meter, HETDEX on HET, and the PFS on Subaru will carry out such surveys in the north; they overlap about half of the LSST extragalactic survey area.

A complementary capability in the Southern Hemisphere would significantly extend this synergy.[8] Such a large, deep spectroscopic survey would also reduce systematic errors associated with weak lensing intrinsic alignments in LSST. This capability would enable other science as well, such as getting spectroscopic redshifts for supernovae and constraining maps of faint galaxies, dark matter halos, and the dark matter environment of clusters. Having an instrument on the Blanco 4-meter such as the DESI spectrograph could also be beneficial in targeting brighter objects. For example, DESI could in principle be moved to the Blanco 4-meter after its Northern Hemisphere survey if that proved cost-effective, technically feasible, and timely.

CONCLUSION: The United States is currently carrying out research and development on DESI, a wide-field highly multiplexed spectroscopic instrument for the KPNO Mayall 4-meter telescope in the Northern Hemisphere. The planned schedule for DESI calls for operations during 2018-2023, completing soon after LSST operations begin.

CONCLUSION: If the DESI project proceeds as planned, then upon completion of its survey from the KPNO Mayall 4-meter, the National Science Foundation (NSF) and the Department of Energy could partner to move DESI to the CTIO Blanco 4-meter (if technically feasible) early in the era of LSST operations in order to enable southern wide-field spectroscopic surveys.

As discussed in Section 4.1, 4-meter-class telescopes fill a niche for a wide range of science, such as narrow band imaging, polarimetry and spectropolarimetry, spectroscopy, and special cadences. Although the Portfolio Review Committee calls for divestment of the Mayall 4-meter,[9] that report notes that it is well suited for wide-field, Northern Hemisphere imaging but that its instrumentation is inferior to DECam. If the Mayall telescope were to continue operating beyond DESI, there would be a benefit to moving DECam there after its survey work on the Blanco

[8] S.J. Schmidt, J.A. Newman, and A. Abate, 2014, "Spectroscopic Needs for Calibration of LSST Photometric Redshifts," white paper submitted to the committee.

[9] National Science Foundation (NSF), 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

4-meter is complete. DECam on the Mayall would provide data that are otherwise unavailable for the northern sky. DECam would go deeper than the SDSS or ZTF, cover more area in a given time than the CFHT Lensing Survey or Subaru Hyper Suprime-Cam, and could in principle be made available to the community (Mayall, along with the now-divested KPNO 2.1-meter, provided most of the Northern Hemisphere public access to U.S. astronomers). DECam could provide photometry for the 20 million galaxies studied by DESI and could be used for a very-wide-area northern weak lensing/cluster survey that would in part complement LSST.

CONCLUSION: If DESI was moved to the Blanco 4-meter, decadal science priorities in the LSST era could benefit from installing DECam on the Mayall 4-meter and using it to carry out wide and deep multi-band imaging surveys in the north.

There are other important U.S.-based resources that have the potential for significant scientific interactions with LSST. The Magellan Consortium[10] operates two 6.5-meter telescopes at Las Campanas. These telescopes have superb imaging, wide fields of view, and a full complement of state-of-the-art imaging and spectroscopic instruments in the optical and near-infrared (IR), including a very successful adaptive optics secondary. Many of the partner institutions have strong connections to LSST. In the past, public access to the Magellan Telescopes was provided by NSF through the Telescope System Instrumentation Program. For very faint or distant objects, there will be strong scientific motivations for supplementary observations with the largest facilities available. These will include GMT in the south, fruitfully located just 1 degree of latitude north of LSST, and TMT along with Gemini North, the Keck 10-meter telescopes, LBT, HET, and MMT in the north, which will overlap with a large percentage of LSST sky coverage.[11] These facilities could be accessed by the community through a telescope time exchange, which is described and recommended in Section 6.2.

LSST Follow-up Observations Beyond OIR

Observatories operating outside the OIR bands are already planning for LSST follow-up observing. The queue-scheduled VLA now spends 10-15 percent of its observing time on time domain projects. The VLA is dynamically scheduled, and

[10] Led by the Carnegie Observatories, with participation from Harvard University, University of Arizona, University of Michigan, and MIT, the consortium includes more than 200 senior astronomers, 100 postdoctoral astronomers, and nearly 100 Ph.D. students.

[11] The white paper submitted to the committee by McConnachie notes that at Maunakea about 1,500 square degrees of the nightly sky covered by LSST is instantaneously available; about 50% of LSST's total 20,000 square degrees sky coverage is accessible at Maunakea (McConnachie et al., 2014, "The Maunakea Spectroscopic Explorer (MSE) Status Update").

its observing schedule can be rapidly altered in response to time-sensitive events. New modes of operation are being designed for the VLA to complement LSST. An interrupt mode is under development that will allow the VLA to be commanded by external triggers from event brokers, giving an on-sky response that is limited only by the slew time of the antennas (typically several minutes). A preliminary version of this mode will be tested in the optical when ZTF comes online.

5.2 COORDINATING TRANSIENT OBSERVATIONS IN THE LSST ERA

The time domain, that is, the detection and study of variable sources, is a strong theme in *New Worlds, New Horizons in Astronomy and Astrophysics*[12] (NWNH) and an extremely important driver for LSST. A major aspect of maximizing the science in the LSST era will be spectroscopic follow-up of transient events. The Lick Observatory Supernova Search (LOSS), Palomar Transient Factory (PTF), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), and the All-Sky Automated Survey for Supernovae (ASAS-SN) have already produced an abundance of new transient discoveries. Soon to come online, the Asteroid Terrestrial-impact Last Alert System (ATLAS), a NASA-funded high-cadence, all-sky monitor, will discover every supernova brighter than 19th magnitude in V-band and all Type Ia supernovae to a redshift $z = 0.01$. The ZTF will feature a camera that can scan 3,750 square degrees of the sky each hour.

LSST will bring a new chapter to time domain astronomy with an unprecedented set of challenges because of its huge rate of discovery of transient objects. It will be both desirable and necessary to achieve a follow-up response time as small as possible to capture the physics of the quickest transient events. As an example, long gamma-ray bursts have 30-second outbursts. Currently, there is virtually no spectroscopy or spectropolarimetry of these objects during their outbursts. There are important and controversial issues about the nature of Type Ia supernova progenitors, the production and distribution of radioactive elements, and the supernova explosions, which need to be addressed within the first hours and days. Perhaps most importantly, but by nature unpredictably, there will be events of unknown origin. LSST will drive changes in the sociology of astronomy in ways that are beginning to happen now, since there will be too much data for any one group to handle. There is a need to develop the software to recognize different types of transients and to coordinate the facilities that can be used for ancillary observations.

[12] NRC, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

Event Brokers

The required response to transient objects can be divided into three regimes according to the scientific goals and technical requirements. Several different categories of transients, with their brightnesses and decay times, are shown in Figure 5.1.

1. *Observations within days to weeks.* These might be traditional targets of opportunity for which an event has occurred that requires an unforeseen observation, such as asteroids, comets, and stars and galactic nuclei in outburst. These events require a policy that allows someone to identify such a need and to make a decision to direct that the observation be obtained.
2. *Observations within hours to a day.* Examples might be supernovae, explosive events that fall between novae and supernovae in peak luminosity and timescale, microlensing detections of exoplanets, and tidal disruption events. For such events, active human intervention to make decisions is appropriate. Current telescopes that claim quick response to targets of opportunity operate in this way. This requires policies that allow intervention and fairly rapid communication.
3. *Observations as rapidly as possible (minutes or less).* Examples are long and short gamma-ray bursts, fast radio bursts, supernova shock breakout, and gravity wave detections. These events require a facility to be connected in such a way that requests for immediate observations flow without human intervention. This is new ground that requires the development of new policy, procedures, and infrastructure for observatory operation essentially as a time domain system.[13]

The PTF, Pan-STARRS, and LCOGT groups have found that complex, dedicated software must be developed to maximize the scientific output of their programs. The task of selecting what is interesting is now the bottleneck, requiring human intervention. With a discovery rate of many events per night, the task of weeding out false-positive events, identifying new variables, deciding which are important for scientific follow-up, and deciding what sort of follow-up is needed cannot be handled efficiently by humans. These groups are developing software known as “event brokers” (or “marshals”) that can automate these processes. This is a complex task that has required many person-years to construct in relatively

[13] T. Tyson, Large Synoptic Survey Telescope, “LSST Time Domain Data Products,” Transient Phenomena in Astronomy and Astrophysics Workshop, October 2014, http://www.gmtconference.org/Tyson_LSST_GMT.pdf.

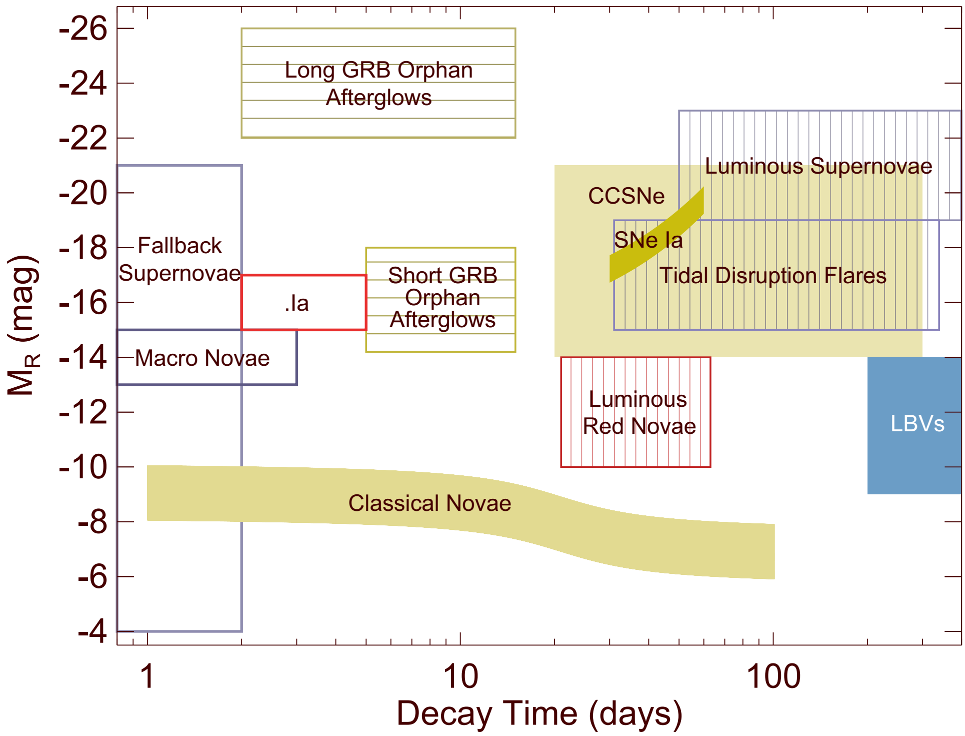

FIGURE 5.1 Different categories of transient objects, with their R-band peak magnitudes as a function of their characteristic decay timescales. SOURCE: A. Rau, S.R. Kulkarni, N.M. Law, J.S. Bloom, D. Ciardi, G.S. Djorgovski, et al., 2009, Exploring the optical transient sky with the Palomar Transient Factory, *Publications of the Astronomical Society of the Pacific* 121:1334.

restricted environments in which each group operates its own discovery and follow-up facilities.[14]

LSST will detect changes in position or flux for around 2 million objects per night and produce an alert for each of them. While the great majority of these will be associated with known objects (variable stars, quasars, main belt asteroids), LSST will also detect a large number of new transient sources per night. There will also be artifacts due to poor subtractions, glints, diffraction spikes, Poisson fluctuations in the background, and other instrumental effects. The LSST project expects to use

[14] See the following white papers submitted to the committee: T. Matheson, S. Ridgway, K. Olsen, and A. Saha, 2014, "Optical/Infra-red Spectroscopy of Transients and Variables in the LSST Era"; R.A. Street, C. McCully, T.A. Lister, D.A. Howell, and J. Parrent, 2014, "Time Domain Astronomy in the Era of LSST"; W.T. Vestrand and P.R. Wozniak, 2014, "The Follow-Up Crisis: Optimizing Science in an Opportunity-Rich Environment."

a combination of improved pixel-level algorithms and, where necessary, machine-learning techniques to reduce the rate of false positives to an acceptable level. Event brokers must aggregate diverse information for each transient detection, allowing the filtering of the huge LSST alert stream into many manageable streams, one for each science project, and generate requests for follow-up observations.

Writing and operating such an event broker is a huge task that must be done to make maximum utility of LSST. There are several current research efforts,[15] such as ANTARES, but the problem is not yet solved. What will be needed for LSST is a single system or a small number of systems that provide a framework that could accommodate a broad range of science applications simultaneously. It is desirable that this work be coordinated so that redundancy is minimized. Ideally, event brokers will identify the necessary follow-up observations and the proper facilities to make those observations, allowing for local weather conditions and other contingencies, and then assign those observing tasks to a range of facilities around the globe within minutes. Coordinating heterogeneous telescopes and instruments will be harder than current smaller, homogeneous efforts.

Follow-up of transients will be much more effective if automated, even roboticized. The need to respond more quickly to gamma-ray bursts and supernovae drove the development of robotic telescopes that could respond with no human intervention. Remote observing would also serve to provide fast response.

The most efficient ancillary facilities to respond to the call from an event broker will enable interruption of observing programs already in place. These calls may be in response to targets of opportunity, which LSST will have in great abundance, or to synoptic observations for which precise timing is key. Other observations may require coordination of several facilities over a variety of wavelengths, on

[15] J.S. Bloom, J.W. Richards, P.E. Nugent, R.M. Quimby, M.M. Kasliwal, D.L. Starr, D. Poznanski, E.O. Ofek, S.B. Cenko, N.R. Butler, S.R. Kulkarni, et al., 2012, Automating discovery and classification of transients and variable stars in the synoptic survey era, *Publications of the Astronomical Society of the Pacific* 124(921):1175-1196; E. Terziev, N.M. Law, I. Arcavi, C. Baranec, J.S. Bloom, K. Bui, M.P. Burse, H.K. Das, R.G. Dekany, A.L. Kraus, et al., 2013, Millions of multiples: Detecting and characterizing close-separation binary systems in synoptic sky surveys, *The Astrophysical Journal* Supplement 206(2):11; H. Brink, J.W. Richards, D. Poznaski, J.S. Bloom, J. Rice, S. Negahban, and M. Wainwright, 2013, Using machine learning for discovery in synoptic survey imaging data, *Monthly Notices of the Royal Astronomical Society* 435(2):1047-1060; T. Matheson, X. Fan, R. Green, A. McConnachie, J. Newman, K. Olsen, P. Szkody, and W.M. Wood-Vasey, 2013, Spectroscopy in the era of LSST, arXiv:1311.2496 [astro-ph.CO]; A. Sahu, T. Matheson, R. Snodgrass, J. Kececioglu, G. Narayan, R. Seaman, T. Jenness, and T. Axelrod, 2014, ANTARES: A prototype transient broker system, *Proceedings of the SPIE* 9149, Observatory Operations: Strategies, Processes and Systems V, 914908; S.T. Ridgway, T. Matheson, K.J. Mighell, K.A. Olsen, and S.B. Howell, 2014, The variable sky of deep synoptic surveys, *The Astrophysical Journal* 796(1):53; G. Elan Alvarez, K. Stassun, D. Burger, R. Wiverd, and D. Cox, 2015, A prototype external event broker for LSST, *American Astronomical Society, AAS Meeting 225*, 336.37.

the ground and in space. Some targets may require new scheduling of multiple observations of the same target for a significant period of time. Queue scheduling may be a special advantage for the required response. On the other hand, the astronomical community is burdened with ToOs; even now there are too many, and they are too disruptive of telescope schedules. There may be a need to develop other strategies. One possibility is to concentrate on one area of the sky. A follow-up telescope could be trained on an LSST field and dedicated for a set period of time so that rapid follow-up of a new discovery could occur with only moderate repositioning of the telescope. Current, smaller-scale surveys (e.g., Gaia, PTF) are already forcing new approaches to many of these problems, and new software tools and policy changes are allowing research groups to enhance coordination between discoveries and follow-up.

Coordination is required to maximize the science in the LSST era.[16] It will not happen without early and intense support. At the national level, the need is to use science requirements to set standards and protocols for event brokers, not their details. This could be a task for the future OIR System coordinator (e.g., National Optical Astronomical Observatory, as described in Chapter 6). Broker efforts need to be coupled with statisticians and computer scientists to learn how to handle sparse data in parameter space and other research-level technical issues. Care must also be taken not to put so much structure in place that the broker system is inflexible, stifling individual initiative. There is a need to correlate with archives, with SDSS being an example of a successful archive in the context of contemporary transient searches. There is also a need for coordination with multi-wavelength observations.

A modular approach to the development of event broker systems, interacting with LSST, would allow different groups to collaborate and build on one another's efforts. Development of such systems could be helped through a solicitation or an existing program, or through fostering public-private collaborations. The committee notes the important self-organization that has occurred in the form of a series of workshops[17] over the past few years.

CONCLUSION: Plans for coordination and communication of transient events are currently inadequate.

[16] See, for example, the discussion on coordination in the white papers submitted to the committee by Walkowicz et al. (L. Walkowicz, A. Mahabal, M. Agüeros, A. Becker, H. Bond, B. Frye, J. Grindlay, V. Kalogera, S. Kanbur, K. Long, M. Moniez, et al., 2014, "OIR Time Domain Astronomy in the Era of LSST"; M. Blanton, K.G. Stassun, and R. Walterbos).

[17] "Hotwiring the Transient Universe," the first of which was held in 2007 and the fourth of which is scheduled for May 2015, organized by LCOGT.

CONCLUSION: Coordination is required to maximize the scientific yield from transients in the LSST era. There is a need for dedicated telescopes and instruments, a system of telescopes, and software to respond efficiently to transients.

RECOMMENDATION: The National Science Foundation should help to support the development of event brokers, which should use standard formats and protocols, to maximize Large Synoptic Survey Telescope transient survey follow-up work.

Needed Capabilities for Transient Follow-up

It will be important to have an appropriate suite of facilities and instruments to respond to significant LSST transients and to coordinate follow-up observations; NSF can employ facilities under its control to maximize the science of transient studies. Especially important are those facilities co-located with LSST, namely, SOAR, Blanco, and Gemini South. Although the focus here is on the southern facilities due to their proximity to LSST, facilities in the Northern Hemisphere, including Gemini North, will cover 30-50 percent of the sky that will be surveyed by LSST, and hence will also have a potential role in LSST follow-up.

Events that pass the LSST event broker system may be relatively rare and thus single objects not requiring a highly multiplexed instrument. A response time of minutes shepherded by an appropriate event broker may be especially valuable for some transient science. Low-dispersion spectrographs are the instrument of choice for first, quick-look spectroscopy and much of the required follow-up.

Spectropolarimetry

Spectropolarimetry is employed in many areas, including studies of active galactic nuclei, galactic and extragalactic magnetic fields, dust and extinction, circumstellar and proto-stellar disks, exoplanets, active stars, and supernovae.[18] It is important that spectropolarimetry remain part of the suite of responses in the LSST era. Current studies show, for instance, that not only are supernovae not round in aspect, but that different chemical species are ejected with different geometries. Total flux spectra cannot provide this sort of information. Coupling the depth information from total flux spectra with the 2D information projected

[18] B.-G. Andersson, A. Adamson, K.S. Bjorkman, J.E. Chiar, D.P. Clemens, D.C. Hines, J.L. Hoffman, T.J. Jones, A. Lazarian, C. Packham, J.E. Vaillancourt, et al., 2014, "The Need for General-Use Polarimeters in the Era of LSST," white paper submitted to the committee.

on the sky with spectropolarimetry yields full 3D, time-dependent, "tomographic" information on the object of study.

Near-IR Capability

Near-IR capability is also very important for transient studies, even when the transient is detected in the optical. As an example, the spectra of supernovae are much less blended in the near-IR than in the optical. This makes identification of certain elements—for instance, helium—much easier to detect in the near-IR. The near-IR is also important to detect weak signatures of hydrogen in otherwise hydrogen-deficient events and to study molecular features such as the CO band head.

SOAR

With its 4.1-meter aperture and potential for rapid response, SOAR could become a prime instrument for early characterization of LSST transients.[19] The critical ingredient provided by SOAR would be early (but then repeated with appropriate, science-driven cadence) low-resolution spectroscopy and spectropolarimetry. This capability would not simply characterize any new event; it would also provide important data on the physical properties and geometrical shape of the outburst at the very times that have been especially elusive with today's technology. The early and ongoing data from SOAR would be archived for later analysis, but the information would also be fed automatically back into the event broker to aid in the subsequent study of the most interesting events with other facilities.

CONCLUSION: It is important for NSF to employ ground-based OIR facilities under its control to maximize the science of transient studies, especially those facilities co-located with LSST.

CONCLUSION: SOAR, with its 4-meter aperture, rapid response, and Southern Hemisphere location, could play an important role (with appropriate spectroscopic capabilities) in follow-up observations of moderate-brightness LSST transients.

[19] See the following white papers submitted to the committee: S. Heathcote, 2014, "Cerro Tololo Inter-American Observatory in the LSST Era"; J.M. Strader, E.F. Brown, L. Chomiuk, E.D. Loh, and S.E. Zepf, 2014, "A View of Astronomy at Universities in the LSST Era."

Gemini South

The operation, especially the queue scheduling, and the near-IR capability of the Gemini telescopes makes them especially powerful facilities to respond to transient targets of opportunity. They need to be coupled to the event broker system to maximize the science output in the LSST era. Gemini South could be an especially important ingredient in the subsequent chain of observations of key transients. With its large aperture, Gemini South could provide timely, higher-resolution spectroscopy, particularly with an instrument with high throughput and moderate resolution. For objects that occur sufficiently far north, Gemini North can also play an important role in this follow-up. For objects in the equatorial swath, the complementary instrument suites in the two Gemini telescopes may be a positive aspect in the follow-up campaigns.

CONCLUSION: Gemini South, with its 8-meter aperture, Southern Hemisphere location, flexible scheduling, and near-IR capability, has the capability to carry out rapid spectroscopic follow-up of a broad array of faint transient events that LSST will detect.

CONCLUSION: The OIR System would benefit significantly if Gemini South was instrumented and operated in a mode that would enable it to carry out rapid follow-up, along with other observational programs (including follow-up of faint, static LSST sources).

RECOMMENDATION: The National Science Foundation should work with its partners in Gemini to ensure that Gemini South is well positioned for faint-object spectroscopy early in the era of Large Synoptic Survey Telescope operations, for example, by supporting the construction of a rapidly configurable high-throughput moderate-resolution spectrograph with broad wavelength coverage.

CONCLUSION: The U.S. has a substantial share of three medium- to large-aperture, open-access facilities in the Southern Hemisphere—Blanco, SOAR, and Gemini South—but they are not operated in a coordinated manner.

CONCLUSION: The U.S. OIR System would benefit if the development of the capabilities of, and the operation of, these three facilities (Blanco, SOAR, and Gemini South) were coordinated to enhance their synergy with LSST.

RECOMMENDATION: The National Science Foundation should ensure via a robustly organized U.S. Optical and Infrared (OIR) System that a fraction

of the U.S. OIR System observing time be allocated for rapid, faint transient observations prioritized by a Large Synoptic Survey Telescope event broker system so that high-priority events can be efficiently and rapidly targeted.

RECOMMENDATION: The National Science Foundation should direct its managing organizations to enhance coordination among the federal components of medium- to large-aperture telescopes in the Southern Hemisphere, including Gemini South, Blanco, the Southern Astrophysical Research (SOAR) telescope, and the Large Synoptic Survey Telescope (LSST), to optimize LSST follow-up for a range of studies.

GSMTs

Follow-up of LSST discoveries will undoubtedly be a rich scientific area for Giant Segmented Mirror Telescopes (GSMTs) as well, and ideally these would factor in to the transient response system. The Giant Magellan Telescope Organization sponsored a community science meeting in Washington, D.C., in October 2014 focusing on transient phenomena[20] that would benefit from GSMT follow-up. As just one example, neutron star-neutron star collisions are associated with short gamma-ray bursts, but they should also produce optical transients that would be very faint and brief. Even when there is a successful strategy for localizing such events, only the largest telescopes will be able to make effective observations in the limited time they are detectable. For this task, the GSMTs will need to be equipped with the capability to do rapid, single-object spectroscopic and spectropolarimetric observations.

[20] Second Annual GMT Community Science Meeting, 2014, http://www.gmtconference.org/, accessed February 1, 2015.

6

Optimizing the U.S. OIR System

The coming decade presents unprecedented opportunities in astronomy that will be enabled by new premier facilities and instruments. Realizing the science goals articulated in *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) and *Vision and Voyages for Planetary Science in the Decade 2013-2022*[2] (VVPS) plus charting compelling new astrophysical frontiers will depend on the continued availability of existing (Chapter 3) and new (Chapter 4) optical and infrared (OIR) capabilities. This section describes a future OIR System composed of individual nodes that is optimized with respect to the needed capabilities, and that coordinates federal and non-federal resource holders to maximize the scientific output. A twofold plan is proposed for (1) system-wide access to telescopes, instruments, and data and (2) strategic instrument development that uses available resources efficiently and promotes the workforce training needed in the areas of hardware, software, and analysis.

6.1 DEFINING THE FUTURE SYSTEM

The impressive current suite of U.S. OIR facilities is the result of decades of remarkable growth in the number and quality of ground-based telescopes and sophisticated instruments that are available to U.S. researchers. In the past two

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[2] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*. The National Academies Press, Washington, D.C.

decades, many 3- to 10-meter-aperture telescopes (WIYN, ARC, SOAR, Gemini, Magellan, Keck II, Subaru, LBT, HET, SALT, GTC, and DCT[3]) have come online, complementing older but still productive facilities at some of the same or nearby sites in California, Hawaii, Arizona, and Chile.

The operators of the U.S. OIR System facilities represent a combination of federal and non-federal institutions. Their diversity of funding sources (multiple federal agencies, state governments, philanthropic foundations, universities, individual donors, and international partners) and talent pools (universities, national labs, international collaborations) is a strength. But there is also a corresponding challenge. The resources made available to astronomy are controlled by a large number of independent organizations; this leads, on the one hand, to healthy competition, but on the other, to sometimes unnecessary duplication of capabilities and lack of coordination.

CONCLUSION: Components of the U.S. OIR System include a wide range of telescope apertures, instruments, and data archives that have been developed and supported in their operations from multiple funding streams.

A strategic plan for the U.S. OIR System must address the projected needs for the future as described in earlier sections—for example, optical direct imaging with coverage and cadences different from LSST, spectroscopic observations at a range of wavelengths and resolutions, spectroscopic multiplexing, narrowband imaging, infrared imaging, high spatial resolution, and high contrast. While many investigations require these capabilities on the largest apertures, medium- and small-sized telescopes are also valuable parts of the U.S. OIR System. The ReSTAR report presented examples ranging across a variety of research areas. Beyond today's science, moreover, access to small- and medium-aperture telescopes is also critical in developing and testing new instruments and technologies and in helping to train the next generation of astronomers.

The National Science Foundation (NSF) currently is struggling with how to balance its ambitious new facilities with the support of the research community and older but still productive facilities.[4,5] The non-federal observatories are also facing

[3] Acronyms not defined in the text, especially those denoting individual instruments and missions, are defined in Appendix C.

[4] National Science Foundation (NSF), 2012, *Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee,* http://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf.

[5] For example, the NSF Portfolio Review Committee recognized the high current importance and potential for future impact of the Mayall 4-meter telescope with its wide-field OIR imaging capabilities, but in the context of funding and other constraints, the PRC recommended NSF divestment of the Mayall (NSF, 2012, *Advancing Astronomy in the Coming Decade*). The plan is now to dedicate the telescope for several years primarily to the DESI experiment run by DOE.

increasing budget and resource limitations. Sustaining, exploiting, and further developing the impressive U.S. OIR System of facilities and people is proving challenging overall, as both the community demand for telescope capabilities and the complexity and cost of instruments have increased. Restriction of U.S. researchers' access to certain components of the U.S. OIR System[6] threatens the potential scientific progress envisaged for the coming decade. Even astronomers with access to private facilities do not, in general, have access to the full complement of instruments and apertures they might need to pursue their research. Large surveys will provide unprecedented amounts of archived data to the community for a wide range of science, and flagship specialized instruments will provide unique data sets. Nevertheless, it is still essential to maintain community access to the diverse suite of capabilities required to pursue the science priorities of NWNH and VVPS and other exciting new science (see Chapters 2 and 4).

CONCLUSION: Because of funding constraints, U.S. astronomers are challenged in their pursuit of decadal goals by having access only to a fraction of the capabilities needed.

The current level of pressure on funding emphasizes the importance of cooperation within the OIR community to consolidate and share resources. Improved partnership in strategic planning, by all segments of the OIR community, will produce a more effective U.S. OIR System of capabilities, as well as free funds for support of premier instruments and telescopes. This cooperation and planning will enable a more efficient and productive research enterprise.

6.2 TELESCOPE TIME EXCHANGE

The current U.S. OIR System operates in a manner such that there are three major categories of access to telescopes: open (through competitive access), pro-

[6] The white paper submitted to the committee by Herbst, coauthored by 20 astronomers from small colleges and universities, stresses the harmful consequences of losing ~75% of the current ~800 nights/year of open telescope access, including most access to 4-meter telescopes in the Northern Hemisphere, if the recommended divestitures in the PRC report (NSF, 2012, *Advancing Astronomy in the Coming Decade*) are implemented (W. Herbst, T. Balonek, J. Bary, R. Cadmus, J. Cannon, W. Cauley, D. Cohen, et al., 2014, "Open Access Facilities in the US OIR System: A Plea from Astronomers at Primarily Undergraduate Institutions"). Further, the PRC report and NWNH noted that ~50% of the U.S. astronomical community using public-access OIR telescopes does not have access to other telescopes. This means that the best science will be more limited and less diverse due to loss of that broader community of proposers. See also the white papers submitted to the committee by Walter and by Liu et al. emphasizing the continued need for access to telescopes of all sizes in order to engage the community (F.M. Walter, 2014; C.T. Liu, B. Willman, J. Pepper, M. Rutkowski, D. Norman, K. Cruz, J. Bochanski, et al., 2014, "Maximizing LSST's Scientific Return: Ensuring Participation from Smaller Institutions").

prietary (through restricted competitive access via ownership or partnership), and collaborative (through colleagues having competitive access). Some astronomers employ all these methods. A fourth means of access is the acquisition of relatively limited amounts of telescope time on privately held telescopes by non-partners through limited agreements. This has made it possible for partner institutions to recoup operating costs in a climate where traditional sources of operations funding are insufficient.

A more effective future U.S. OIR System would make use of telescope time drawn from all of the cooperating facilities in the U.S. OIR System that would be allocated to high-ranking science from U.S. PIs in a community-wide proposal process, with a unified time allocation committee (TAC) (perhaps using the existing machinery of National Optical Astronomical Observatory [NOAO]).[7] Resources would be granted to the institutions or facilities providing the telescope time. The allocated resource might be in the form of funding for purposes that include covering the cost of operations, facilitating ongoing improvement of equipment, or building new instruments. Any of these options would benefit the U.S. OIR System as a whole under this model. Alternately, the allocated resource such as telescope time, equipment, data access, or infrastructure access at alternate nodes in the system could be bartered among the institutions.

CONCLUSION: A telescope time exchange would broaden the suite of capabilities available to U.S. astronomers and would foster the complementarity of capabilities developed by different elements of the U.S. OIR System. These benefits would enable more of the goals of the decadal surveys to be accomplished.

Interested observatories would participate, for example, by first offering some percentage of their nights for competitive open access, for exchange with NSF (through barter or limited partnership agreements, as appropriate for the observatory) or trade with other observatories having different capabilities. NSF would be a catalytic force in enabling a cooperative system. Having the full range of telescope apertures and instruments available to the community and driven by competitive proposals would enable the best science to be matched to the best-suited capabilities. A functional OIR System of facilities, developed and operated by components funded both federally and non-federally, could provide the requisite community access and satisfy in the modern era the original motivation for the creation of

[7] The envisioned mechanics of NOAO proposal processing were operational in the era of TSIP and could be revitalized and expanded to cover the suite of future participants in the U.S. OIR System. See, for example, the white paper submitted to the committee by Walter et al., who suggest that NOAO coordinate such a program (F.M. Walter, T. Armandroff, R. Bernstein, M. Bolte, W. Herbst, P. Lira, M. Margulis, et al., 2014, "AURA Observatory Council Views on the National Observatory").

NOAO. The panel discussion with over 10 private observatory directors at the OIR committee's second meeting[8] emphasized the willingness of private observatories to participate in such a system provided the incentives for open access to their telescopes are sufficient. An OIR System that optimizes astronomy resources through more cooperative efforts stands to benefit everyone in the field.

The program envisaged here would be broader than the now-canceled Telescope System Instrumentation Program (TSIP) that enabled some competitive public telescope access in exchange for federal funds for instrumentation or, in later rounds, for operations costs. The ALTAIR report and several white papers[9] comment on the usefulness and the scientific and demographic success of the former TSIP and mention the possibility of expanding that idea. The new program proposed herein should open up access to a broad spectrum of non-federal facilities that would participate as nodes in the future OIR System based on the mutual benefits. The proposed program also satisfies the balance recommended in the Portfolio Review Committee report[10] regarding access, training, and inclusiveness.

CONCLUSION: NSF participation in a telescope time exchange program would restore to U.S. astronomy an important fraction of the science otherwise lost as a consequence of the divestment of NOAO facilities.

Implementation of a new U.S. OIR System telescope access plan would rely on supply and demand plus empowerment of an organization to coordinate the matching of science proposals and capabilities (in the form of either observing time to acquire new data or access to existing data). In advance of the science proposal call, each participating facility would negotiate with the organizing entity for the amount of time that could be available and the price. For example, a particular observatory might offer that 10-30 percent of science nights be made available through the common proposal process. The total amount used would depend both on the demand and on the level of NSF funding available. If the demand fell below the minimum level desired for participation by that observatory (say, 10% in this case), the observatory could opt out. Multi-year agreements would enable

[8] Agenda and participants listed at http://sites.nationalacademies.org/BPA/BPA_087934; see also T.E. Armandroff, 2014, "Input from McDonald Observatory to the Committee on a Strategy to Optimize the U.S. OIR System in the Era of the LSST for Questions 3 and 10."

[9] See the following white papers submitted to the committee: Armandroff, 2014, "Input from McDonald Observatory to the Committee on a Strategy to Optimize the U.S. OIR System in the Era of the Large Synoptic Survey Telescope for Questions 3 and 10"; J. Cohen and C. Martin, 2014, "The Crucial Role of W.M. Keck Observatory in the U.S. Astronomical System"; A.P. Marscher, T. Bania, E. Blanton, T. Brainerd, K. Brecher, D. Clemens, C. Espaillat, et al., 2014, "White Paper on the Future of Ground-Based OIR Astronomy in the US"; N.B. Suntzeff, 2014; Walter et al., 2014, "AURA Observatory Council Views on the National Observatory."

[10] NSF, 2012, *Advancing Astronomy in the Coming Decade.*

proposals of scale and significant scope to be considered and awarded for telescope, instrument, or data access and would also help in the planning by observatories.

Federal resources allocated to facilities based on community science proposals solicited from the entire U.S. community would come only after a peer-review competitive process. NOAO, with its experience handling TACs for a variety of telescopes, would be the logical body to manage the review and the time allocation. NOAO also could be empowered as the negotiating body for the availability of nights or data access that are on offer from the non-federal resource holders. The AURA Observatory Council reiterates the idea of NOAO coordinating the broad range of capabilities in the U.S. OIR System.[11]

The TACs would be made aware that they have two resources to manage when ranking the science priorities among the proposals received: the available telescope nights or data access offered by the nodes, and the support including NSF funding for their access. Recent sales of telescope time by private observatories suggest that NSF support on the order of $1 million to $2 million per year, for example, would provide access to 20-40 nights per year on 8-meter-class telescopes and proportionately more on smaller telescopes, which are also an important component of the system. This level of NSF support would represent less than half of what was until recently spent operating telescopes on Kitt Peak, or alternatively, less than half of what was spent on TSIP. Support could be increased as funding allows.

Implementation of an effective exchange will require common understanding of issues such as the value of various assets within the system and the timescales on which they are reassessed.[12] Given the complex array of assets and plausible incentives, the exchange program as envisioned will almost certainly require a ramp-up, perhaps preceded by a pilot phase.

CONCLUSION: The long experience of NOAO in competitive allocation of telescope time makes it a natural choice to participate on behalf of NSF in an exchange program, and to host and facilitate the exchange.

[11] Walter et al., 2014, "AURA Observatory Council Views on the National Observatory."

[12] For example, TSIP had methods for assigning a value estimate for the cost of a night at a facility based on the amortized telescope and instrument development and the annual operations cost. The general problem of management of scientific resources involving coordination by a central broker for limited exchanges is discussed by Ledyard (J.O. Ledyard, D. Porter, and A. Rangel, 1994, Using computerized exchange systems to solve an allocation problem in project management, *Journal of Organizational Computing* 4(3):271-296). The methods were applied successfully to trades among teams of scientists involved in the instruments on the Cassini mission to Saturn and in secondary payloads on the Space Shuttle, with either allocated or otherwise owned fixed resources. Other similar, currently operating, scarce resource marketplaces involve, for example, computational grid access, electromagnetic spectrum allocation, and industrial pollution permits. The analogy to telescope nights will require further study.

RECOMMENDATION: The National Science Foundation (NSF) should direct the National Optical Astronomical Observatory to administer a new telescope time exchange with participating observatories of the U.S. Optical and Infrared System. Observatory representatives would barter facilities, swap instruments, or engage in limited term partnerships for telescope time or data access on behalf of their respective constituencies, as appropriate, and NSF would barter telescope time or data access or engage in limited term partnerships to carry out proposals competed through a system-wide time allocation committee.

6.3 FORMULATING A PLANNING PROCESS

A coordinated approach to telescope, instrument, and data access as described above can be either part of, or separate from, a strategic planning process in which the community addresses the highest-priority science objectives of the coming decade through the cooperation of all capable components of the U.S. OIR System, both federal and non-federal. An organized U.S. OIR System composed of complementary capabilities operating under a living roadmap would be the best way to capitalize on the system resources and address the science questions highlighted in NWNH and VVPS.

The decadal surveys specify which flagship and moderate-scale facilities need to be built and operated. Determining the full suite of moderate- and smaller-scale capabilities required to pursue the wide range of frontier science goals needs to be carried out on a finer scale and updated more frequently than the decadal surveys. This committee report provides recommendations in Chapters 4 and 5 for specific near-term capabilities. For the future, ongoing detailed planning for the OIR System of capabilities and, importantly, implementation of those plans on timescales of a few years can be executed by the federal and non-federal observatories and facilities that together make up the OIR System. The process does, however, need to be empowered by federal funding agencies.

CONCLUSION: Execution of an OIR System strategic plan to identify and develop highest-priority new peer-reviewed capabilities—for example, new instruments and software—would help address near-term decadal science needs.

Such a planning process can be successful only if instrument and software builders have an active role in shaping recommendations, and thus a stake in seeing the recommendations carried out.

One approach to this fine-scale identification of needed OIR capabilities would be sets of periodic (e.g., biennial or triennial) workshops, focusing on decadal survey science or technical areas, with the goal of mapping frontier scientific investigations onto existing telescopes and instruments. Prioritized instruments would be matched to the telescope best suited for the desired capabilities, regardless of whether the telescope was public or private; if private, the community would gain some open-access nights to it. Examples of similar past open, science-based activities include planning for instruments for Gemini Observatory, the ALTAIR and ReSTAR studies, and the 2008 adaptive optics (AO) roadmap. Workshops lead to understanding both of the existing capabilities for which ongoing support is needed and of the missing capabilities and their science drivers. The workshop approach also establishes broad consensus on a roadmap for developing the necessary new capabilities. A critical component is the assignment of priorities to the existing and proposed capabilities. Appropriate prioritization enables resource decisions to carry out the investigations that will address decadal survey science.

The task of organizing this system-wide strategic process, including running meetings or workshops and generating and publicizing reports, could be taken on by NOAO. The system organizing committee could be a standing committee with rotating membership, representative of all segments of the community. The workshops could be narrow or broad, as needed, and the organizing committee would turn the outcomes into a prioritized plan that is viable and consistent with decadal needs. As an example of the utility of such activities, past system development activities led or managed by NOAO included TSIP, which over its lifetime provided 453 new (previously inaccessible to the broad U.S. community of professional astronomers) nights on large telescopes and 13 new instruments, and distributed \$33 million in funds to facilities for instrument building and telescope operations.[13]

CONCLUSION: A component of the process for generating and updating the system plan could be a periodic forum to review the capabilities that need to be sustained or developed through partnered or independent investment, by NSF and other partners, in the U.S. OIR System. NOAO could facilitate the meeting by a system organizing committee, chosen to represent all segments of the community.

The successful evolution of the U.S. OIR System depends on implementing the roadmap that results from the consensus telescope and instrument plan, not just creating the roadmap. Implementation will require two ingredients: (1) endorsement of the process and the plan by all the stakeholders including funding agencies, the federal and non-federal observatories, and the broad community and (2) directed resources allocated to the specific development activities called for by the plan.

[13] National Optical Astronomy Observatory, "TSIP Funding and Public Access Summary," http://ast.noao.edu/system/tsip/more-info/funding-summary, accessed March 1, 2015.

The resources necessary to provide the important new capabilities within the OIR System are considerable. State-of-the-art astronomical instruments, even for mid-sized telescopes, cost millions of dollars, while premier "flagship" instruments on the largest current telescopes can cost tens of millions and those for the Giant Segmented Mirror Telescopes (GSMTs) will approach $50 million or more. Past studies that have proposed programs aimed at strategic investment in OIR instrumental capabilities (*Astronomy and Astrophysics in the New Millennium*[14] [AANM] and NWNH) have put estimates of about $10 million per year on the required funding level coming from outside the observatories. Such an investment in the OIR System by federal funding agencies would leverage the other considerable resources that the non-federal observatories have acquired, including the private funds that produced the telescopes themselves. Outside investment in future instrumentation for GSMTs will most likely be necessary because of scope, complexity, and cost and is a means to procure broader astronomical access, as recommended in Section 4.3.

For efficient and effective development of the capabilities of the OIR System, the processes for both the development of the roadmap and its implementation must be endorsed collectively by all stakeholders: NSF, the federal and non-federal observatories, and the broader U.S. astronomical community. In practice, the roadmap will account for only a fraction of the development activities that are supported and carried out at the individual OIR System nodes. Roadmap execution should not impede small creative projects with much shorter timescales than the decadal initiatives. The agreed-upon plan will optimize the use of federal resources by drawing on the various strengths within the OIR System as they are needed to realize decadal science priorities.

Rather than a detailed listing of what the rules of this program might be in practice, here are a few proposed principles to guide its definition:

1. The development of the strategic plan, and, in particular, the coordination of science needs with new capabilities, must be an activity in which the entire community is invited to participate. Organizations that provide significant resources to the overall evolution of the OIR System must be included in the oversight of the program.
2. Peer-reviewed selection is required at each stage at which proposals are competed.

CONCLUSION: Development and implementation of new capabilities will require (1) funding (to the level available), (2) groups capable of carrying

[14] NRC, 2000, *Astronomy and Astrophysics in the New Millennium*, The National Academies Press, Washington, D.C.

out the technical work effectively, and (3) telescopes on which to deploy and use new instruments.

RECOMMENDATION: The National Science Foundation should direct the National Optical Astronomical Observatory (NOAO) to administer an ongoing community-wide planning process to identify the critical Optical and Infrared System capabilities needed in the near term to realize the decadal science priorities. NOAO could facilitate the meeting of a system organizing committee, chosen to represent all segments of the community, which would produce the prioritized plan. NSF would then solicit, review, and select proposals to meet those capabilities, within available funding.

The current incarnation of the Mid-Scale Innovations Program (MSIP) includes within its scope both relatively large projects for new telescopes and major instruments, and smaller proposals to provide the kind of telescope access (or data access) that previously was part of TSIP (optical) and the University Radio Observatories (radio) programs. The MSIP funding pool is not large enough to accommodate everything that was envisioned by NWNH beyond the strategic new instrumentation at the mid-scale level. Furthermore, MSIP is not structured in a way that reliably ensures that funding will be directed toward the strategic goals described in this report.

Another consideration is that the federal funding provided to support development of new capabilities within the U.S. OIR System often will constitute partnerships with non-federal observatories. This public-private relationship has in the past been difficult for NSF to accommodate within its proposal-driven review and selection process.

The committee believes that having mid-scale proposals compete against each other in MSIP is a good idea. But it also believes that MSIP is not well structured to meet decadal priorities. NSF Division of Astronomical Sciences (AST) might consider whether there are mechanisms within the MSIP categories for preferentially funding capabilities that would further decadal survey priorities in general (not just for OIR). Within OIR, these capabilities could be identified by the ongoing planning process described here. Note that the original recommendation by the AANM decadal survey was that "all facilities, whether nationally or independently operated, be viewed as single integrated systems—one for optical and infrared astronomy, one for radio astronomy, and one for solar astronomy. The committee recommends that NSF AST implement a plan for ground-based astronomy that reflects an integrated view of independent and national observatories and the funding available from government and private sources."[15] With this AANM

[15] NRC, 2000, *Astronomy and Astrophysics in the New Millennium*, p. 182.

recommendation in mind, it is conceivable that, for planning small and mid-size projects for science called out by decadal surveys, fields beyond OIR could also engage in community planning processes. Then (assuming a sufficient funding line for MSIP), a portion of MSIP funds could be allocated for anything suggested by the community at large, and a portion could be allocated for capabilities identified by the community planning to meet decadal objectives.

CONCLUSION: MSIP is not structured in a way that supports strategic decisions, nor is its funding pool large enough that strategic decisions could be easily integrated into its funding process.

6.4 BUILDING THE U.S. OIR SYSTEM

NSF receives guidance from the decadal surveys for using its resources to achieve science priorities. In the model outlined above, NSF would manage its program to support peer-reviewed highly ranked proposals that request funding for OIR System access to telescopes, instruments, and data (Section 6.2) and to support development of new near-term capabilities specified by the planning process, developed with the decadal science in mind (Section 6.3). A more integrated and self-regulated approach might be even more effective. System coordination that includes both elements outlined above—the access and the strategic instrumentation development—could be undertaken by a single organization charged with responsibility for carrying out all aspects of the coordination.

For example, a focused workshop could be organized to produce an updated plan in a specific decadal science priority area; the plan would specify an instrument to be built; a solicitation would produce proposals to develop such an instrument; the instrument would be constructed and placed at the optimum telescope within the system; time would be made available through the telescope time exchange; and access would then be granted to this premier instrument to the best science proposals. As noted in Sections 6.2 and 6.3, all interested stakeholders would be represented in this process.

The organization charged with overall system coordination for the telescope time exchange and planning process should be one that can bring a common understanding and institutional memory to the process. NOAO has a scientific, technical, and administrative staff that has effectively carried out tasks much like those described above as would be needed for a system managing organization. With appropriate thought about how to implement this program, including endorsement by the non-federal observatories partners in the OIR System and at the direction of NSF, NOAO could assume its natural role as the coordinator of this revitalized OIR System on behalf of NSF and the entire community. This is essentially the role that was desired for NOAO by both AANM and NWNH.

CONCLUSION: Creation and operation of the Telescope Time Exchange, OIR System strategic planning, and implementation of the plan might be most effective if carried out as an integrated program. NOAO has successfully conducted activities like these in the past and would be the logical choice to undertake this program, representing NSF interests.

CONCLUSION: A wide range of participants will have a stake in the success of this activity. It is critical that all these stakeholders have a role in its oversight.

6.5 THE INTERNATIONAL SCENE

While the United States has continued to produce outstanding telescopes, instruments, and astronomy results over the past several decades, international colleagues have accelerated their developments and now rival or surpass the United States in several areas. A few examples of some of the international facilities and future planning for them are mentioned here.

The European Southern Observatory (ESO) has four 8.2-meter telescopes at Paranal Observatory in Chile, each equipped with three different instruments. Its relatively stable funding line over several years enables ESO to plan efficiently for future instruments, such as the SPHERE spectropolarimeter with high-contrast AO and the ESPRESSO echelle spectrograph for radial velocity measurements. Part of ESO's mission is to organize collaborations; its instruments are developed in a coordinated way, with most built by consortia of institutes. ESO has a suite of smaller telescopes as well, which are mostly run by ESO member consortia. The ESO community has thus maximized its combined resources by having a strong support network of partnerships for instrument development and small and medium telescope operations, with ESO concentrating on operating and upgrading the largest facilities. The E-ELT, a planned 39-meter telescope, is expected to have first light in the early 2020s.

The National Astronomical Observatories of the Chinese Academy of Sciences, the National Institutes of Natural Sciences/National Astronomical Observatory of Japan, and the Indian Institute of Astrophysics have joined TMT as partners, while the Association of Canadian Universities for Research in Astronomy joined as associate member. Astronomy Australia Limited, Australian National University's Research School of Astronomy and Astrophysics, the Korea Astronomy and Space Science Institute, and the Sao Paulo Research Foundation of Brazil are international partners in GMT.

China operates the 4.3-meter Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST), which is a wide-field telescope with 4,000 simultaneous optical fibers. Japan operates the 8.2-meter OIR Subaru Telescope on Maunakea in Hawaii, with several key state-of-the-art instruments. A forthcoming Prime Focus Spectrograph (PFS) with 2,400 fibers will complement the HyperSuprime Camera, and will be a critical instrument for LSST follow-up. A planned 6.5-meter telescope in Chile (Tokyo Atacama Observatory, TAO) is in the final design phase. Mexico is planning construction of a 6.5-meter telescope (San Pedro Martir Telescope, SPMT) in Baja, California.

The Canary Islands Institute for Astrophysics runs the 10.4-meter Gran Telescopio Canarias (GTC), on La Palma, in addition to the 4.2-meter William Herschel Telescope (WHT). It is in the process of building EMIR, a wide-field multi-object infrared spectrograph, similar to its optical equivalent, the Optical System for Imaging and Low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS). It also plans a new multi-object spectrograph, WEAVE, for the WHT, which it will use for LSST follow-up.

Many countries engage in long-term planning for capabilities and prioritized science activities. There is a long history of collaborations and partnerships between other countries and international institutions and U.S. federal and private facilities. Many are planning to be partners with LSST. Much of the key LSST science does not require rapid follow-up, so non-member countries can still benefit from LSST by accessing its publicly available data after the propriety period has ended. Nonetheless, access to time-critical events might be of sufficient value to barter LSST data in an exchange program.

As recommended in NWNH,[16] it would be useful for the United States to engage in periodic international discussions in order to consider additional ways of collaboration and coordination to maximize scientific output from facilities. Such collaborations can either be formal (as with TMT and GMT) or informal, such as trading access to unique or complementary capabilities. At the International Astronomical Union XXIX General Assembly in Hawaii in August 2015, a focus meeting on Global Coordination of Ground and Space Astrophysics and Heliophysics will consider ways forward for international collaboration. In the future, NOAO, as coordinator for the U.S. OIR System, could help facilitate such discussions.[17]

CONCLUSION: NOAO could play a potentially beneficial role as a facilitator of discussions between the U.S. OIR System and other countries' observatories in order to pursue possible international telescope time exchanges.

[16] NRC, 2010, *New Worlds, New Horizons*, p. 28.

[17] See presentations by D. Silva on the future of NOAO and by H. Hammel on the role of AURA (D. Silva, National Optical Astronomy Observatory, "NOAO Today and Tomorrow," presentation to the committee on October 12, 2014; H.B. Hammel, Association of Universities for Research in Astronomy, "AURA Perspective," presentation to the committee on October 13, 2014; both are available at http://sites.nationalacademies.org/BPA/BPA_087934#presentations).

7

Epilogue

The landscape for astronomy today holds much promise, as many decadal survey science priorities are under way or coming to fruition. At the same time, the federal financial outlook is weaker than it was when *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) and *Vision and Voyages for Planetary Science in the Decade 2013-2022*[2] (VVPS) were completed. There are opportunities to realize greater achievement of science goals through a coordination of federal and non-federal resources, as envisioned in a telescope and data-access exchange program described in Section 6.2. There are also scientific advantages to instituting community-wide ongoing strategic planning (discussed in Section 6.3) for medium- and small-scale initiatives on shorter time scales than a decade, even while the largest projects historically take longer than a decade to complete.

Part of the charge of this committee was to consider the instrumentation, data management, and support capabilities needed in the near term. The report's conclusions for near-term requirements have been detailed in previous sections, and as mentioned, the recommendations include a wide-field highly multiplexed spectrograph; coordination of telescopes and software and instrument capabilities (such as high-throughput single-object spectrographs on large telescopes) for transient follow-up; and technology development in detectors, adaptive optics (AO),

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[2] NRC, 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C.

and radial velocity. These are the types of activities that the committee envisions would be part of the discussions of future strategic planning by the U.S. Optical and Infrared (OIR) System organizing committee.

The scientific harvest of Large Synoptic Survey Telescope (LSST) data will be magnified through coordinated follow-up efforts in software and observing capabilities. Discoveries through the synergies of telescopes spanning a range of capabilities will be better enabled in a revitalized U.S. OIR System in which telescope and data access are better facilitated. Finally, the astronomical enterprise will be enriched by developing and supporting instrumentation and software expertise and technology. The recommendations in this report suggest a federal investment of $10 million to $20 million per year.

For convenience, all conclusions and recommendations presented in the report are collected here in order of presentation.

3.1 Current Telescopes and Instruments in the Optical and Infrared System

CONCLUSION: Interest from and telescope usage by a large, diverse, and active community of high-quality researchers are correlated with high-impact scientific output.

3.3 Future Data Management Needs

CONCLUSION: Consistent with NWNH recommendations and federal mandates, a data archive that is publicly accessible and well curated is a commendable central goal for every major survey from a public or private facility.

CONCLUSION: LSST will accumulate more than 20 TB of data per night during an anticipated 10-year lifetime. The LSST project will generate sophisticated, well-calibrated databases that will enable many projects without further data processing. Generating higher-level data and algorithms is not part of the LSST project charge.

CONCLUSION: LSST will provide a data center to serve alerts, images, and catalogs, with 10 percent of the center's resources (CPU cycles and database storage) reserved for the community. The data center will be colocated with publicly available petascale computing facilities at the National Center for Supercomputing Applications.

CONCLUSION: LSST will use standard protocols to serve data where available (e.g., VOEvent) and will work with the community to evolve and establish future standards.

CONCLUSION: Making effective use of petabyte-scale databases ("big data") requires new skills, and the astronomical community working in this area needs to continue to develop algorithms and procedures for data processing and analysis to take advantage of the next generation of data sets.

CONCLUSION: The scientific return from large surveys (both ground- and space-based) would be maximized if their data and catalogs were made widely available using standard protocols, with appropriate data products made available for copying or downloading when possible. Because of the volumes of data involved, the centers serving the data would be most useful if appropriate public computing cycles and storage were available to users to take data-intensive analysis to the data instead of requiring redundant copies of the data on local computing resources.

3.4 Training in Observing, Instrumentation, and Software

CONCLUSION: Specialized training in general observing, instrumentation, software, and data analysis techniques is essential for ensuring that the next generation of astronomers has the requisite skills to accomplish the best science.

RECOMMENDATION: The National Science Foundation (NSF) should support a coordinated suite of schools, workshops, and training networks run by experts to train the future generation of astronomers and maintain instrumentation, software, and data analysis expertise. Some of this training might best be planned as a sequence, with later topics building on earlier ones. NSF should use existing instrument and research programs to support training to build instruments.

3.5 Maintaining Instrumentation and Software Expertise

CONCLUSION: Long timescales for complex projects and oversubscription of instrument funding lines discourage early career specialization in instrumentation.

CONCLUSION: NSF Advanced Technologies and Instrumentation and Major Research Instrumentation funding is inadequate to support the rising cost of small- and medium-instrument projects.

CONCLUSION: There is inadequate funding for instrumentation programs. This is largely the result of the increasing cost and complexity of instruments for the next generation of telescopes, with funding gaps between projects. The increased complexity of instruments also requires stronger engineering and project management components than in the past, and it is rare to have this as part of the training in astronomy instrumentation programs.

CONCLUSION: The need to complete complex expensive projects means that less funding is going toward explorative technology development.

4.1 Science-Driven Needs for OIR Instrument Capabilities

CONCLUSION: Because of the diversity of critical astronomical studies in NWNH and VVPS, a variety of instruments, some already available, on large and medium telescopes will be integral to successful progress in understanding the universe in the next decade. These include a wide-field highly multiplexed moderate-resolution optical/near-IR spectrograph, a high-throughput, moderate-resolution spectrograph, a high-resolution integral field unit optical or infrared spectrograph, optical and near-IR imaging with adaptive optics, and extreme precision Doppler spectroscopy and AO coronagraphy.

CONCLUSION: Small- and medium-aperture telescopes are useful for a range of science endeavors that require spectroscopy, spectropolarimetry, narrow-band imaging, or a different cadence than LSST.

4.2 Technology Development

CONCLUSION: Science realized today relies on the investments made in the past both on specific telescope and instrument development and more general technology development. Going forward, a similar mix of near-term and intermediate-term efforts is required in order to maintain healthy progress in astronomy.

RECOMMENDATION: The National Science Foundation (NSF) should continue to invest in the development of critical instrument technologies, including detectors, adaptive/active optics, and precision radial velocity measurements. NSF should also use existing instrument and research programs to support small-scale exploratory programs that have the potential to develop transformative technologies.

4.3 Importance of the Giant Segmented Mirror Telescopes

CONCLUSION: With their monumental gains in sensitivity and angular resolution, the Giant Segmented Mirror Telescopes (GSMTs) are poised to revolutionize the understanding of key astrophysical phenomena as well as to open new, unexpected frontiers. They are likely to be underfunded once they become operational.

CONCLUSION: The GSMTs will be crucial for detailed follow-up investigations of many discoveries from existing and planned facilities, including the Atacama Large Millimeter/submillimeter Array, Gaia, LSST, the James Webb Space Telescope, Euclid, and the Wide-Field Infrared Survey Telescope, and will make major contributions to many of the next decade's key science questions, including the nature of debris disks, the physics of planet formation, the growth of black holes, and the advent of the first galaxies.

RECOMMENDATION: The National Science Foundation should plan for an investment in one or both Giant Segmented Mirror Telescopes in order to capitalize on these observatories' exceptional scientific capabilities for the broader astronomical community in the Large Synoptic Survey Telescope era—for example, through shared operations costs, instrument development, or limited partnerships in telescope or data access or science projects.

5.1 Follow-Up Telescope and Instrumentation Needs

CONCLUSION: There is currently no wide-field, highly multiplexed spectroscopic capability on medium- or large-aperture telescopes in the Southern Hemisphere in the U.S. OIR System.

CONCLUSION: Wide-field, highly multiplexed spectroscopic capabilities on medium- and large-aperture telescopes in the Southern Hemisphere in the LSST era would be of great benefit to the U.S. OIR System, enabling a wide variety of science including follow-up spectroscopy of LSST targets.

RECOMMENDATION: The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way.

CONCLUSION: The United States is currently carrying out research and development on Dark Energy Spectroscopic Instrument (DESI), a wide-field highly multiplexed spectroscopic instrument for the Kitt Peak National Observatory (KPNO) Mayall 4-meter telescope in the Northern Hemisphere. The planned schedule for DESI calls for operations during 2018-2023, completing soon after LSST operations begin.

CONCLUSION: If the DESI project proceeds as planned, then upon completion of its survey from the KPNO Mayall 4-meter, NSF and the Department of Energy could partner to move DESI to the Cerro Tololo Inter-American Observatory Blanco 4-meter (if technically feasible) early in the era of LSST operations in order to enable southern wide-field spectroscopic surveys.

CONCLUSION: If DESI was moved to the Blanco 4-meter, decadal science priorities in the LSST era could benefit from installing Dark Energy Camera on the Mayall 4-meter and using it to carry out wide and deep multi-band imaging surveys in the north.

5.2 Coordinating Transient Observations in the LSST Era

CONCLUSION: Plans for coordination and communication of transient events are currently inadequate.

CONCLUSION: Coordination is required to maximize the scientific yield from transients in the LSST era. There is a need for dedicated telescopes and instruments, a system of telescopes, and software to respond efficiently to transients.

RECOMMENDATION: The National Science Foundation should help to support the development of event brokers, which should use standard formats and protocols, to maximize Large Synoptic Survey Telescope transient survey follow-up work.

CONCLUSION: It is important for NSF to employ ground-based OIR facilities under its control to maximize the science of transient studies, especially those facilities colocated with LSST.

CONCLUSION: The Southern Astrophysical Research (SOAR) telescope, with its 4-meter aperture, rapid response, and Southern Hemisphere location, could play an important role (with appropriate spectroscopic capabilities) in follow-up observations of moderate-brightness LSST transients.

CONCLUSION: Gemini South, with its 8-meter aperture, Southern Hemisphere location, flexible scheduling, and near-IR capability, has the capability to carry out rapid spectroscopic follow-up of a broad array of faint transient events that LSST will detect.

CONCLUSION: The OIR System would benefit significantly if Gemini South was instrumented and operated in a mode that would enable it to carry out rapid follow-up, along with other observational programs (including follow-up of faint, static LSST sources).

RECOMMENDATION: The National Science Foundation should work with its partners in Gemini to ensure that Gemini South is well positioned for faint-object spectroscopy early in the era of Large Synoptic Survey Telescope operations—for example, by supporting the construction of a rapidly configurable high-throughput moderate-resolution spectrograph with broad wavelength coverage.

CONCLUSION: The United States has a substantial share of three medium- to large-aperture, open-access facilities in the Southern Hemisphere—Blanco, SOAR, and Gemini South—but they are not operated in a coordinated manner.

CONCLUSION: The U.S. OIR System would benefit if the development of the capabilities of, and the operation of, these three facilities (Blanco, SOAR, and Gemini South) were coordinated to enhance their synergy with LSST.

RECOMMENDATION: The National Science Foundation should ensure via a robustly organized U.S. Optical and Infrared (OIR) System that a fraction of the U.S. OIR System observing time be allocated for rapid, faint transient observations prioritized by a Large Synoptic Survey Telescope event broker system so that high-priority events can be efficiently and rapidly targeted.

RECOMMENDATION: The National Science Foundation should direct its managing organizations to enhance coordination among the federal components of medium- to large-aperture telescopes in the Southern Hemisphere, including Gemini South, Blanco, the Southern Astrophysical Research (SOAR) telescope, and Large Synoptic Survey Telescope (LSST), to optimize LSST follow-up for a range of studies.

6.1 Defining the Future System

CONCLUSION: Components of the U.S. OIR System include a wide range of telescope apertures, instruments, and data archives that have been developed and supported in their operations from multiple funding streams.

CONCLUSION: Because of funding constraints, U.S. astronomers are challenged in their pursuit of decadal goals by having access only to a fraction of the capabilities needed.

6.2 Telescope Time Exchange

CONCLUSION: A telescope time exchange would broaden the suite of capabilities available to U.S. astronomers and would foster the complementarity of capabilities developed by different elements of the U.S. OIR System. These benefits would enable more of the goals of the decadal surveys to be accomplished.

CONCLUSION: NSF participation in a telescope time exchange program would restore to U.S. astronomy an important fraction of the science otherwise lost as a consequence of the divestment of National Optical Astronomical Observatory (NOAO) facilities.

CONCLUSION: The long experience of NOAO in competitive allocation of telescope time makes it a natural choice to participate on behalf of NSF in an exchange program and to host and facilitate the exchange.

RECOMMENDATION: The National Science Foundation (NSF) should direct the National Optical Astronomical Observatory to administer a new telescope time exchange with participating observatories of the U.S. Optical and Infrared System. Observatory representatives would barter facilities, swap instruments, or engage in limited term partnerships for telescope time or data access on behalf of their respective constituencies, as appropriate, and NSF would barter telescope time or data access or engage in limited term partnerships to carry out proposals competed through a system-wide time allocation committee.

6.3 Formulating a Planning Process

CONCLUSION: Execution of an OIR System strategic plan to identify and develop highest-priority new peer-reviewed capabilities—for example, new instruments and software—would help address near-term decadal science needs.

CONCLUSION: A component of the process for generating and updating the system plan could be a periodic forum to review the capabilities that need to be sustained or developed through partnered or independent investment, by NSF and other partners, in the U.S. OIR System. NOAO could facilitate the meeting by a system organizing committee, chosen to represent all segments of the community.

CONCLUSION: Development and implementation of new capabilities will require (1) funding (to the level available), (2) groups capable of carrying out the technical work effectively, and (3) telescopes on which to deploy and use new instruments.

RECOMMENDATION: The National Science Foundation should direct the National Optical Astronomical Observatory (NOAO) to administer an ongoing community-wide planning process to identify the critical Optical and Infrared System capabilities needed in the near term to realize the decadal science priorities. NOAO could facilitate the meeting of a system organizing committee, chosen to represent all segments of the community, which would produce the prioritized plan. NSF would then solicit, review, and select proposals to meet those capabilities, within available funding.

CONCLUSION: The Mid-Scale Innovations Program is not structured in a way that supports strategic decisions, nor is its funding pool large enough that strategic decisions could be easily integrated into its funding process.

6.4 Building the U.S. OIR System

CONCLUSION: Creation and operation of the Telescope Time Exchange, OIR System strategic planning, and implementation of the plan might be most effective if carried out as an integrated program. NOAO has successfully conducted activities like these in the past and would be the logical choice to undertake this program, representing NSF interests.

CONCLUSION: A wide range of participants will have a stake in the success of this activity. It is critical that all these stakeholders have a role in its oversight.

6.5 The International Scene

CONCLUSION: NOAO could play a potentially beneficial role as a facilitator of discussions between the U.S. OIR System and other countries' observatories in order to pursue possible international telescope time exchanges.

Appendixes

A

Request for White Papers

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

August 27, 2014

Division of Engineering and Physical Sciences
Board on Physics and Astronomy
Committee to on a Strategy Optimize the U.S. OIR System in the Era of the LSST

REQUEST FOR WHITE PAPERS

The National Research Council's Committee on a Strategy to Optimize the U.S. Optical and Infrared (OIR) System in the Era of the Large Synoptic Survey Telescope is charged with identifying the principal federal and non-federal capabilities in the U.S. OIR System and making strategic recommendations to optimize the system for the best science return. The committee finds it vital to its deliberations to collect input from the astronomy community in the course of its work.

The committee has developed a list of questions about the OIR system and we invite any researcher or group in the community to answer any or all of these questions in a brief (1-2 pages) White Paper.

We are developing an input submission site to facilitate your responses. This site will go live soon. We will post an announcement that the submission site is live on the committee's website (not through an AAS email). We ask for all input to be submitted by 9:00 a.m. EDT on Monday, October 6, 2014.

Understanding the community's perspectives is crucial to the committee's task and the resulting report to the National Science Foundation, so we thank you in advance for your generous assistance in this regard.

All submissions will be made publicly available through The National Academies' Public Access Records Office per FACA Section 15 and will be posted on the committee's public website, as well. Please direct all questions to the National Research Council (OIR_Study@nas.edu).

The committee's questions to the community are as follows:

1. What O/IR capabilities are you using, are you planning to use, and will you need through the LSST era?
2. Do you have access to the O/IR capabilities you currently need to conduct your research, e.g. through a proposal process, through collaborators, or via data archives? If not, what is missing?
3. Comment on the need for the U.S. community's access to non-federal O/IR facilities up to 30 meters in size.
4. What could be done, outside of increased funding, that would enable the U.S. astronomical community to realize the goals of the decadal surveys at OIR wavelengths?
5. What is the role that a national observatory should have in an effective ground-based OIR system?
6. What are the U.S. long-term data management, archiving, and mining needs in ground-based O/IR astronomy, including those for LSST?
7. Given the increasing complexity of astronomical instrumentation, where should new major instruments be built (e.g. universities, national labs, collaborations)? How much instrument duplication is desirable or sustainable across different facilities of similar aperture?
8. How can the community ensure that future generations of astronomers have relevant instrumentation, observing, and software skills for the frontier science of tomorrow?
9. Comment on any needed evolution in human astronomical infrastructure, that is, the efficiency of sustaining instrumentation, data, or software teams in centers of excellence relative to assembling the needed skill sets from across the community.
10. What types of scientific and observing coordination among the various NSF telescopes (including Gemini and LSST) and non-federal facilities are the most important for making scientific progress in the next 10-15 years? How can such coordination best be facilitated?

WHITE PAPER SUBMISSIONS

The following white papers were submitted to the Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope, National Research Council, Washington, D.C.:[1]

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B

Observatory Demographics

The data in Table B.1 were submitted by the observatories at the request of the National Research Council. The information received was not uniform; most columns represent an estimate rather than an exact count. Some categories such as personnel were difficult for the observatories to estimate, since some people had responsibilities in more than one area, and some resources were shared. For some categories, observatories did not track the numbers. Some results are for 1 quarter, and were scaled up to 1 year. In some cases, only total numbers were given over the lifetime of the observatory. Nonetheless, despite being non-uniform, the data provide useful information on the range of people involved at different observatories and the wealth of results based on data obtained at each observatory.

TABLE B.1 Observatory Demographics

Observatory	FTE Scientists[a]	FTE Mountain[b]	FTE Engineers, Software Specialists, and Instrumentalists[c]	Papers from Observatory Data per Year[d]	Proposals Accepted at Each Telescope per Year[e]	Different PIs per Year[f]	Total Investigators per Year[g]
APO ARC 3.5 m	0.25	8.5	3.5	50	240	120	400
APO Sloan (SDSS) 2.5 m	6	20.5	8.5	600	n.a. - 3 surveys	3	500
CFHT	9	4.5 day crew	17	127	187	172	627
CTIO SMARTS—ALL	1.21	5.0	4.8	65	121	74	352
CTIO	9.05 functional; 4.45 research	26	30	Blanco: 76	42	35	
				SOAR 41	24	21	
				SMARTS 13	26	23	
Discovery Channel	12 at Lowell	8	7	3 refereed, 7 notices	108 + 12 outreach	100	Unknown
Gemini	50 science 7 TT; 25 research; <8 FTE research	10-20 day crew 2 night crew	80 in N+S	202	150-200, 2/3 from US	300 (all partners)	>1,400 (all partners)
GMT	12 PhDs	84, 2 shifts	33	Not yet built	Not yet in operation	n.a.	n.a.
IRTF	4	6	8	105	150	100	300
Keck	12	33	31	3,741 total	233	226	535
KPNO	5 functional, 2 research	12	21	Mayall: 96	68	68	308
				WIYN: 44	24 (NOAO)	24	103
				2.1 m: 49	15 (14A only)	15 (14A only)	54 (14A only)

continued

TABLE B.1 Continued

Observatory	FTE Scientists[a]	FTE Mountain[b]	FTE Engineers, Software Specialists, and Instrumentalists[c]	Papers from Observatory Data per Year[d]	Proposals Accepted at Each Telescope per Year[e]	Different PIs per Year[f]	Total Investigators per Year[g]
LBT	11	20	25	50	n.a.	85	n.a.
LCOGT	6	2	16	30	70 (network)	50	100
Magellan	4	27	10	200	350	200	500
McDonald[h] HET	4	19	10	22	30	30	30
McDonald 2.7 m	3	8 plus physical plant and other jobs not directly related to telescopes	5	50	45	50	75
McDonald 2.1 m	Shared with 2.7 m	Shared with 2.7 m	Shared with 2.7 m	20	12	25	40
MMT	5	10	9	100	137	86	292
Palomar	1	22	6	n.a.	120	80	150
SALT	24	17	37	20	184	104	334
WIYN	3.5	3.5	4.5	40; 2.8 PhD	60	40	150

NOTE: Acronyms are defined in Appendix C.
[a] Approximate number of full-time equivalent scientists who work at the observatory.
[b] Approximate number of full-time equivalent personnel who work on the observatory mountain.
[c] Approximate number of full-time equivalent engineers, software specialists, and instrumentalists who work at the observatory.
[d] Approximate annual number of peer-reviewed publications based on data acquired at the observatory.
[e] Approximate number of proposals accepted at each different telescope at the observatory per year.
[f] Approximate number of different principal investigators who observe each year.
[g] Approximate total number of observers at the observatory each year.
[h] For McDonald Observatory, the HET upgrade currently going on has an additional number of contract people working on it. HET is run by McDonald for a consortium of 5 institutions. McDonald does not track papers by users of the 2.7- and 2.1-m telescopes, so these are estimates.

C

Acronyms

2MASS	Two Micron All Sky Survey
4MOST	4-metre Multi-Object Spectroscopic Telescope
AAAC	Astronomy and Astrophysics Advisory Committee
AANM	*Astronomy and Astrophysics in the New Millennium* (2000 astronomy and astrophysics decadal survey report)
ACCORD	AURA Coordinating Council of Observatory Research Directors
AGN	active galactic nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
ALTAIR	Access to Large Telescopes for Astronomical Instruction and Research
ANTARES	Arizona—NOAO Temporal Analysis and Response to Events System
AO	adaptive optics
AODP	Adaptive Optics Development Program (NSF)
APO	Apache Point Observatory
APOGEE	APO Galactic Evolution Experiment
ARC	Astrophysical Research Consortium
ARCONS	Array Camera for Optical to Near-IR Spectrophotometry
ASAS-SN	All-Sky Automated Survey for Supernovae
ASM	Adaptive Secondary Mirrors
AST	Division of Astronomical Sciences (NSF)
ATI	Advanced Technologies and Instrumentation (NSF)

ATLAS	Asteroid Terrestrial-impact Last Alert System
AURA	Association of Universities for Research in Astronomy
BAO	baryon acoustic oscillation
BoRG	Brightest of Reionizing Galaxies Survey
BOSS	Baryon Oscillation Spectroscopic Survey
BPA	Board on Physics and Astronomy (NRC)
CAA	Committee on Astronomy and Astrophysics (NRC)
CADC	Canadian Astronomy Data Centre
CANDELS	Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CFHT	Canada France Hawaii Telescope
CLASH	Cluster Lensing and Supernova Survey with Hubble
CPU	central processing unit
CTIO	Cerro Tololo Inter-American Observatory
DCT	Discovery Channel Telescope
DECam	Dark Energy Camera
DEIMOS	Deep Imaging Multi-Object Spectrograph
DES	Dark Energy Survey
DESC	Dark Energy Survey Collaboration
DESI	Dark Energy Spectroscopic Instrument
DKIST	Daniel K. Inouye Solar Telescope
DOE	Department of Energy
DPOSS	Digitized Palomar Observatory Sky Survey
DR12	Data Release 12
eBOSS	extended Baryon Oscillation Spectroscopic Survey
E-ELT	European Extremely Large Telescope
EMIR	Espectrógrafo Multi-objecto InfraRojo
EPDS	Extreme Precision Doppler Spectrometer
ESA	European Space Agency
ESI	Echellette Spectrograph and Imager
ESO	European Southern Observatory
ESPRESSO	Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations
FOV	field of view
GMACS	GMT wide-field multi-object optical spectrograph
GMOS	Gemini multi-object spectrograph

GMT	Giant Magellan Telescope
GMTO	Giant Magellan Telescope Organization
GPI	Gemini Planet Imager
GRB	gamma ray burst
GSMT	Giant Segmented Mirror Telescope
GTC	Gran Telescopio Canarias
HEASARC	High Energy Astrophysics Science Archive Research Center
HET	Hobby-Eberly Telescope
HETDEX	Hobby-Eberly Telescope Dark Energy Experiment
HFF	Hubble Frontier Fields
HIRES	High Resolution Echelle Spectrometer
HST	Hubble Space Telescope
HUDF12	Hubble Ultra Deep Field 2012
IFU	integral field unit
INT	Isaac Newton Telescope
IPAC	Infrared Processing and Analysis Center
iPHAS	INT Photometric H-Alpha Survey
iPTF	Intermediate Palomar Transient Factory
IR	infrared
IRSA	Infrared Science Archive
IRTF	Infrared Telescope Facility
IVOA	International Virtual Observatory Alliance
JWST	James Webb Space Telescope
KCWI	Keck Cosmic Web Imager
KI	Keck Interferometer
KPNO	Kitt Peak National Observatory
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic Telescope
LBNL	Lawrence Berkeley National Laboratory
LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LCOGT	Las Cumbres Observatory Global Telescope
LEECH	LBT Exozodi Exoplanet Common Hunt
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational-Wave Observatory
LOSS	Lick Observatory Supernova Search
LRIS	Low-Resolution Imaging Spectrometer

LSST	Large Synoptic Survey Telescope
MARVELS	Multi-object APO Radial Velocity Exoplanet Large-area Survey
MAST	Mikulski Archive for Space Telescopes
MESA	Modules for Experiments in Stellar Astrophysics
MKID	microwave kinetic inductance detector
MMT	Multiple Mirror Telescope (former)
MOONS	Multi-Object Optical and Near-infrared Spectrograph
MOS	multi-object spectroscopy
MOSFIRE	Multi-Object Spectrometer for Infra-Red Exploration
MREFC	Major Research Equipment and Facilities Construction (NSF)
MRI	Major Research Instrumentation
MSE	Maunakea Spectroscopic Explorer
MSIP	Mid-Scale Innovations Program (NSF)
MUSE	Multi-Unit Spectroscopic Explorer (ESO)
NASA	National Aeronautics and Space Administration
NCSA	National Center for Supercomputing Applications
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIRC	Near Infrared Camera
NIRC2	Near Infrared Camera 2
NIRSPEC	Near Infrared Echelle Spectrometer
NN-EXPLORE	NASA-NSF Exoplanet Observational Research
NOAO	National Optical Astronomical Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array
NWNH	*New Worlds, New Horizons in Astronomy and Astrophysics* (2010 astronomy and astrophysics decadal survey report)
O/IR	optical and infrared
OIR	optical and infrared
OSIRIS	Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy
OSTP	Office of Science and Technology Policy
Pan-STARRS	Panoramic Survey Telescope & Rapid Response System
PB	petabyte (= 1 million gigabytes = 10^{15} bytes)
PFS	Prime Focus Spectrograph

PI	principal investigator
PRC	Portfolio Review Committee
PS1	Prototype Telescope for Pan-STARRS
PTF	Palomar Transient Factory
ReSTAR	Renewing Small Telescopes for Astronomical Research
REU	Research Experiences for Undergraduates (NSF)
RMS	radio, millimeter, and submillimeter
SALT	Southern African Large Telescope
SDSS	Sloan Digital Sky Survey
SEEDS	Strategic Exploration of Exoplanets and Disks with Subaru
SEGUE	Sloan Extension for Galactic Understanding and Exploration
SKA	Square Kilometer Array
SLAC	Stanford Linear Accelerator Center
SMARTS	Small and Moderate Aperture Research Telescope System
SOAR	Southern Astrophysical Research telescope
SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research
SPMT	San Pedro Martir Telescope
SSB	Space Studies Board (NRC)
TAC	time allocation committee
TAO	Tokyo Atacama Observatory
TB	terabyte (=1,000 gigabytes = 10^{12} bytes)
TESS	Transiting Exoplanet Survey Satellite
TIO	TMT International Observatory
TMT	Thirty Meter Telescope
TNO	Trans-Neptunian Object
ToO	target of opportunity
TSIP	Telescope System Instrumentation Program
ugrizy	Set of broadband optical filters from ultraviolet through near-infrared
UKIDSS	UKIRT Deep Infrared Deep Sky Survey
UKIRT	United Kingdom Infrared Telescope
URO	University Radio Observatories
USVAO	U.S. Virtual Astronomical Observatory (formerly the National Virtual Observatory
UVEX	UV-Excess Survey of the Northern Galactic Plane
VISTA	Visible and Infrared Survey Telescope for Astronomy

VLA	Very Large Array
VLT	Very Large Telescope
VO	virtual observatory
VVPS	*Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011 planetary science decadal survey report)
WEAVE	WHT Enhanced Area Velocity Explorer
WFIRST	Wide-Field Infrared Survey Telescope
WHT	William Herschel Telescope (Canary Islands 4.2-m telescope)
WIRO	Wyoming Infrared Observatory
WISE	Wide-Field Infrared Survey Explorer
WIYN	Wisconsin-Indiana-Yale-NOAO Consortium 3.5-m telescope
ZTF	Zwicky Transient Facility