Key extracts from the US Decadal Survey (Astro2020) report regarding the Giant Magellan Telescope (GMT)

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Because of the powerful potential that large (20–40 m) telescopes with diffraction-limited adaptive optics have for astronomy, and because of the readiness of the projects, the survey's priority for a frontier ground-based observatory is a significant U.S. investment in the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) projects, ideally as components of a coordinated **U.S. Extremely Large Telescope Program (ELT) program**. These observatories will create enormous opportunities for scientific progress over the coming decades and well beyond, and they will address nearly every important science question across all three priority science areas.

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The U.S. Extremely Large Telescope Program (Highest Priority in the Ground-Based Frontier Category)

Because of the transformative potential that large (20–40 m) telescopes with diffraction-limited adaptive optics have for astronomy, and because of the readiness of the projects, the survey committee's top recommendation for frontier ground-based observatories is investment in the U.S. ELT program. The U.S. ELT program is made up of three elements: the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab). The primary mirror of the GMT has a total diameter of 24.5 m and the telescope has a 25 arcmin field-of- view (FOV). The GMT will be located at the Las Campanas Observatory in Chile. The TMT primary mirror has a diameter of 30 m, and the telescope has a 20 arcmin FOV. The TMT will either be sited on Maunakea in Hawaii, or at Roque de los Muchachos Observatory on La Palma in the Canary Islands. These observatories will create enormous opportunities for scientific progress over the coming decades and well beyond, and they will address nearly every important science question across all three priority science themes. Both projects are essential for keeping the U.S. community's global scientific leadership, providing important synergistic capabilities that complement those planned for the European ELT. However, both projects have significant remaining risks primarily associated with the need to raise additional private or international contributions. The success of at least one of these projects is absolutely essential if the United States is to maintain a position as a leader in ground-based astronomy. The objective is to achieve a time share that is equivalent to 25 percent in each telescope. If only one project is viable, then a larger fraction on that telescope is required to meet the survey's scientific goals, with the aim of achieving an NSF share up to 50 percent time in that project. (Sec.7.6.1.1)

Decision Rules: Successful completion of an external review that will determine the financial viability of both projects, final site selection (in the case of TMT), development of an appropriate management plan and governance structure, and appropriate plans for public access and data archiving.

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7.6.1.1 The U.S. Extremely Large Telescope Program

The U.S. ELT Program as proposed to the survey is made up of three elements: the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and NSF's National Optical-Infrared Astronomy Research Laboratory (NOIRLab) (See Figure 7.7). The primary mirror of the GMT has a total diameter of 24.5 meters and the telescope has a 25 arcmin field-of-view (FOV). The GMT will be located at the Las Campanas Observatory in Chile. The majority of the GMT partners are U.S. institutions, with international partners in Australia, Brazil, and Korea. The TMT primary mirror has a diameter of 30 meters and the telescope has a 20 arcmin FOV. The TMT will either be sited on Maunakea in Hawaii, or at Roque de los Muchachos Observatory on La Palma in the Canary Islands. The majority of the TMT partners are international, with the participation of institutions in the United States, Canada, China, India, and Japan. For comparison, the European Southern Observatory (ESO) is building the ESO ELT on Cerro Armazones in Chile with a 39.3 m diameter and a 10 arcminute FOV, with first light expected in 2028. Both the TMT and the GMT are well into development; both projects have mature designs and have commenced fabrication of key elements, although challenges remain. They are expected to commence operations in the mid 2030's, contingent on a U.S. funding commitment.

The scientific potential of the ELTs is vast. The combination of large collecting area (4-9 times that of a 10m Keck telescope) and diffraction-limited imaging (0.01-0.02" FWHM with adaptive optics in the near-IR) provides observational capabilities unmatched in space or the ground, and opens an enormous discovery space for new observations and discoveries not yet anticipated. A resolution of

0.01” (12 times that of the Hubble telescope at similar wavelengths) projects to a linear scale of 25 km at Jupiter, 1 AU for a protoplanetary disk at distance 100 pc, 0.8 pc at the distance of the Virgo Cluster, and 60 pc for galaxies at redshift z=2.5 (comparable to the scales resolved by ground-based telescopes with natural seeing at Virgo). For unresolved sources the sensitivity of these telescopes scales as their diameter to the fourth power, a gain of 36–81 times over current 10 m telescopes. The large collecting areas of the telescopes also makes them powerful spectroscopic machines, especially for high-resolution spectroscopy where measurements are often limited by detector noise.

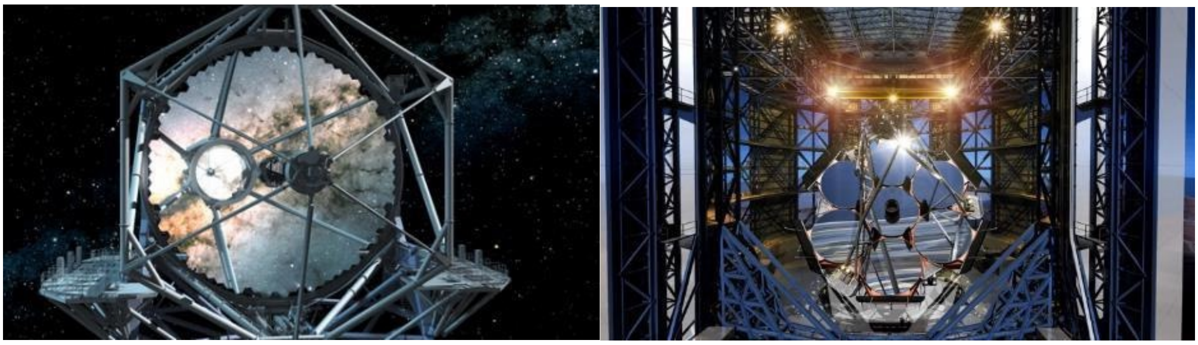

FIGURE 7.7 The Thirty Meter Telescope mirror (left) and the Giant Magellan Telescope mirror (right). Both ground-based projects are at an advanced stage of development and have commenced construction of their primary optics. SOURCE: *Left:* https://www.tmt.org/page/uselt. Courtesy of the TMT International Observatory. *Right:* Courtesy– GMTO Corporation.

This powerful combination of capabilities can be brought to bear on nearly all of the important science questions laid out by this decadal survey, across all three of our key science themes. They will be able to detect, image, and characterize temperate rocky planets around low-mass stars, measure their atmospheric compositions including searches for oxygen, image protoplanetary disks, and through precision radial velocity measurements measure the masses of the planets, vital information only possible with the ELTs. Fundamental physics will be probed through a variety of pathways, including measurements of stars orbiting the Milky Way’s central black hole SgrA*, to perform tests of relativity and gravity. Measurements of the cosmic expansion rate using different methods (variable stars, gravitational lensing, merging neutron star “standard sirens”) will test for the reality of the current Hubble tension and reveal whether the current ΛCDM cosmological model fully describes the expansion.

Measurements of the faint spectra of gamma-ray bursts and supernovae beyond redshifts z=10 will probe both the physics of stellar explosions at early cosmic times and probe this epoch of reionization itself. The impacts of the ELTs for revealing the workings of the Cosmic Ecosystem promise to be especially powerful. These telescopes alone will have the sensitivity to make spectroscopic measurements of the faintest galaxies, stellar explosions, and black holes detected by JWST; the result of these studies will be a record over cosmic time of the buildup of matter, stars, heavy elements, and the assembly of the galaxies themselves from hundreds of thousands of years after the Big Bang to the present. Likewise, these telescopes will have the unique ability to trace the chemical and dynamical buildup of the Milky Way and nearby galaxies out to the Virgo cluster, through deep high-resolution imaging and spectroscopy of their oldest stars. Many of these unique capabilities complement those of our top-ranked space project, the IR/O/UV space telescope, extending the powerful synergies between the ground-based 6-10 m telescopes and HST over the past 30 years (and soon with JWST and the Roman telescope). As demonstrated by the 16 6.5-12m OIR telescopes currently in operation around the world (not counting the Rubin Observatory or others under construction), the versatility of these instruments and the large range of top-priority scientific applications will more than fully occupy even three ELTs for decades.

Conclusion: Because of their transformative scientific potential, as well as readiness, the success of at least one U.S. ELT is a critical priority for investment for ground-based astronomy in the coming decade.

Although the U.S. astronomy community would benefit enormously by an NSF investment in even one of the TMT or GMT, there is considerable benefit to pursuing a coherent two-telescope U.S. ELT Program that would combine capabilities of both A two-telescope U.S. ELT program would offer full-sky coverage, important for leveraging the current U.S. multi-billion dollar bi-hemispheric system of ground-based OIR and radio astronomical facilities (JVLA and the future ngVLA in the north, ALMA and the Vera Rubin Observatory in the south) and assure observations of rare objects (e.g., nearby habitable exoplanets, rare classes of transient events) regardless of where they lie in the sky. Complementary instrumentation on the two telescopes developed in a coherent manner in partnership with NOIRLab would significantly increase the scientific reach of the overall U.S. ELT program. Investing in two telescopes would also maximize the total number of nights of public-access observing time—potentially as much as 200 nights per year—and far more than remain available for NSF partnership on either of the observatories alone.

The enormous scientific potential of the ELTs has also been recognized overseas. Several international organizations are partners in the GMT and TMT project, and in 2008 a European Astronet decadal study identified an ELT as one of its top priorities (along with a Square Kilometer Array radio telescope project). ESO now is constructing a 39 m ELT in Chile, with planned commissioning later in this decade. NSF participation in a U.S. ELT program will position the U.S. community to take full advantage of the promise of these facilities. Although smaller in aperture the TMT and GMT offer a number of unique capabilities, including fields of view 4-6 times larger than the ESO ELT (facilitating multi-object spectroscopy), and high-resolution first-generation spectrometers capable of carrying out groundbreaking observations of exoplanets, ancient stars, and the circumgalactic and intergalactic media, key elements of the Habitable Worlds and Galaxy Growth priority areas. These capabilities are regarded less as competitive advantages than as powerful synergies between complementary facilities which will hasten the advancement of the science frontier objectives highlighted in this survey.

As proposed to this survey, the U.S. ELT program would be comprised as a collaboration between the GMT and TMT projects with the NSF NOIRLab. NOIRLab would provide proposer and user support, public data products and archiving, broaden participation in U.S. ELT science, foster research inclusivity, and engage and represent the whole U.S. community in the U.S. ELT governance and scientific planning. NSF partnership would leverage major investments by universities and foundations ($1.5 billion), and international partners ($1.2 billion), and assure that the fruits of these revolutionary facilities are shared by the largest possible community of researchers and students in the United States.

The Panel on Optical and Infrared Observations from the Ground (OIR) assessed the programmatic and technical risks and cost of both the GMT and TMT separately, and both underwent an independent TRACE analysis. The TRACE construction cost estimates of $2.4 billion and $3.1 billion for GMT and TMT respectively are within 20 percent of the project cost estimates ($2 billion and $2.65 billion), which is within the uncertainties. While there are technical challenges for both projects, solutions appear to be in-hand. TMT has the added risk that the site has not yet been selected, adding cost and schedule uncertainty. However, the biggest risk for both projects is the large gap between commitments in-hand from the partners, and what is required to complete the projects, even with a significant federal investment by NSF of $0.8 billion per project. This programmatic risk is significant, and the TRACE analysis gave both projects a medium-high programmatic risk rating.

The scientific potential of the ELTs is so compelling, and the science so broad, that ideally community access would be at least 25 percent on each of the ELTs (as proposed to the survey). If, however, programmatic or financial challenges preclude the viability of one of the projects, the survey recommends that NSF invest in at least one ELT, with a share of the time proportional to the fractional federal investment in constructions and operations.

Recommendation: The National Science Foundation (NSF) should achieve a federal investment in at least one and ideally both of the two extremely large telescope projects— the Giant Magellan Telescope and the Thirty Meter Telescope, with a target level of at least 25 percent of

the time on each telescope. If only one project proves to be viable, NSF should aim to achieve a larger fraction of the time, in proportion to its share of the costs and up to a maximum of 50 percent.

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7.8.1.1 MREFC Program

The budget profile analysis shown in Figure 7.8 presents the program outlined in the roadmap of new ground-based major projects in terms of the NSF share of expected program/project cost, and it compares the total cost with the budget projection provided by NSF. The chart runs through FY2041 to capture the expected completion of the ngVLA. The TRACE cost and schedule estimates are used for construction, and project or Program Panel estimates for operations. In some cases, the phasing and durations were adjusted to manage several factors: approximate budget, technology development/readiness, and other programmatic factors. For example, the U.S. ELT program, consisting of TMT and GMT, was spread out over an additional 2 years, lowering the peak spending proposed by the projects, but consistent with the OIR program panel's judgement related to the rapidity with which NSF funding could be provided. For the ngVLA, the RMS panel recommended an additional 2 years of design and development relative to plans provided by the project prior to any major ramp up of construction efforts, and we incorporate that into this analysis. The NSF MREFC share assumed for the ELTs is 25 percent of the total construction costs for each telescope, for CMB-S4 40 percent of the costs are assumed to be borne by NSF (60 percent by the DOE), and for the ngVLA, the NSF share is assumed to be 75 percent of total costs, with 25 percent to be identified in the future international partners. These fractional funding levels were adopted from the project white papers and presentations. The MREFC budget profile also includes current commitments and a growing wedge for the agency-wide MSRI mid-scale programs as provided to us by NSF. Mid-scale projects are discussed elsewhere, but the committee assumed approximately 15 percent of the NSF-wide MSRI budget line shown here might be successful AST projects. The remainder of the mid-scale funding would need to come out of the AST budget to achieve the total $50 million a year target.

FIGURE 7.8 Recommended program for the National Science Foundation (NSF) MREFC. The chart assumes that the agency-wide midscale MSRI funding wedge given to the survey by NSF is realized. It also includes agency-wide prior commitments, and the new NSF construction funding required to realize the large AST projects recommended by the survey. The solid line shows the MREFC budget guidance provided to the survey by NSF through 2030, and extrapolated beyond this using 2.7% inflation. Note that for CMB-S4, U.S. ELTs, and the ngVLA, which have additional contributions from other agencies and partners, only the NSF-share of the total funding is shown. The operations costs for new facilities are included in the budget chart for NSF AST; see Figure 7.9.

K. Report of the Panel on Optical and Infrared Observations from the Ground

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EXECUTIVE SUMMARY

We face a future filled with extraordinary opportunities. New ground-based Optical-Infra-Red (OIR) observational facilities are central to addressing the most pressing and fundamental questions in astronomy and astrophysics, as assessed by the six Science Panels of the Astro2020 decadal survey.[1] The importance of some of these questions transcends the boundaries of science: How did we get here? Are we alone? To exploit these opportunities, the United States—which has led the world for decades in ground-based OIR astronomy—must overcome some enormous challenges.

First, to maintain a leadership position in the 2030s and beyond, investments of an unprecedented scale by NSF in ground-based OIR astronomy will be required. The panel has carefully evaluated the proposal to Astro2020 to create and fund a unified U.S. Extremely Large Telescope Program (U.S.-ELTP) that will combine the resources and capabilities of NSF's NOIRLab, the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT). Combined with Key Science Programs facilitated by NSF's National Optical-Infrared Research Laboratory (NOIRLab), this U.S.-ELTP will create a system for the broad U.S. community that is fully competitive with, and complementary to, the European Extremely Large Telescope (E-ELT), and one that maximizes synergies with the current U.S. multi-billion-dollar bi-hemispheric system of ground-based astronomical facilities. The programmatic challenges facing the U.S.-ELTP are daunting indeed, and it is not at all clear that there will be adequate financial capacity to complete the construction and fund the operations of this two-telescope system. The panel has reached the consensus that the rewards of a successful outcome are high enough for NSF and the other GMT and TMT partners to be given the opportunity to try to achieve this success. The panel believe a zero-ELT outcome will gravely damage the U.S. astronomy community for decades.

The second challenge is posed by the need to exploit the immense investment that has already been made in the past 30 years to create a powerful and flexible U.S. ground-based OIR system. This is particularly pressing because the scientific payout from a U.S.-ELTP is over a decade away. The panel has reviewed fifty thoughtful white papers from the ground-based OIR community, and has identified a set of thematic areas in which relatively modest investments (e.g., at or below the level of the NSF Mid- scale Research Infrastructure-2 (MSRI-2) program) in existing telescopes could reap major returns during the 2020s. The panel also highlights several opportunities in this medium-scale range to build new special-purpose telescopes or telescope arrays. In some cases, these could be interagency projects (e.g., NSF and NASA, or NSF and DOE). In other cases, they could be in the context of an international partnership. Last, the panel emphasizes the importance of modest strategic investments in technology development and software, and in the further development of the systems-level approach to optimizing the performance of the OIR system in an era of time-domain/multi-messenger astrophysics.

For this plan to succeed, there needs to be a fundamental change in the way in which the federal, state, and private funding sources for ground-based OIR facilities interact. A broad partnership is necessary for the United States to maintain leadership. NSF will need a major boost in the Major Research Equipment and Facilities Construction Funding (MREFC) line, a robust MSRI program, and a new model for how operations of new facilities are paid for. If we can accomplish all of this, we can fully reap the extraordinary scientific harvests for decades to come.

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K.1.1 Setting the Stage

It is axiomatic that major scientific discoveries are driven by new technology, and in no field is this clearer than in astronomy. Galileo Galilei did not invent the telescope, but he was the first to use it to observe the sky and record his discoveries. His book *The Starry Messenger* (1610) reported on his observations of the Moon, Jupiter, and the Milky Way. These observations revolutionized our understanding of the cosmos and ushered in centuries of discoveries to come based on ever-more-powerful telescopes. The era of astrophysics can be said to have begun roughly a century ago, launched by the construction of large telescopes armed with spectrographs. For many decades, the United States was the unrivaled leader in the construction and utilization of such facilities, from the 100" at Mount Wilson (1917) to the 200" at Mount Palomar (1948). This U.S. leadership was made possible largely through an unmatched level of philanthropy.

Such days are over. Starting in the late 1960s the level of funding provided by the U.S. federal government and of other nations produced a suite of telescopes that matched the capabilities of the largest private/state-funded facilities. This situation has continued into the current era of very large telescopes, which started to come into operation in 1990s. The importance of the next generation Extremely Large Telescopes (ELTs) has been recognized for at least 20 years, and indeed an ELT was the top ground- based recommendation of the 2000 decadal survey. Yet, as we survey the landscape today, we see that the scale of investment needed to construct and operate the next generation of Extremely Large Telescopes (ELTs) is severely straining the financial model that has served the U.S. astronomical community so well for over a century (which has largely segregated private/state-, and federally funded telescopes). Initially two competing ELT projects with major U.S. involvement emerged: the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Since the previous decadal survey, *New Worlds, New Horizons* (NWNH), there has been an enormous amount of work done to retire the most challenging technical risks to the construction of GMT and TMT. These two projects have now joined forces with NSF's NOIRLab to propose a unified U.S.-ELT program seeking substantial federal funding for, and providing access to both ELTs by the U.S. community.

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K.3 THE U.S. EXTREMELY LARGE TELESCOPE PROGRAM

K.3.1 Introduction

We stand at a watershed moment. A new generation of Extremely Large Telescopes is essential to answering the most important questions in astronomy and astrophysics in the 2030's and the decades that follow. It seems clear that without a major federal investment, the two ELT programs with U.S. stakeholders, the Giant Magellan Telescope (GMT) and the Thirty-Meter Telescope (TMT), will both fail, severely damaging U.S. astronomy for decades.

At this pivotal time, the two ELT projects have joined forces with NSF's NOIRLab to propose a radically new concept to Astro2020: a unified U.S.-ELT Program that will provide the broad U.S. astronomy community with access to both GMT and TMT in exchange for a substantial federal investment in the ELTs, and with an interface to this broad community provided by NOIRLab. The panel then considered two stark choices: Endorse an unprecedented level of NSF investment and a revolutionary new "business model" to capitalize on this investment, or cede U.S. leadership in the frontier science enabled by ELTs for decades to come. The panel argues below in favor of the first choice on the basis of the review of a proposed U.S.-ELT Program uniting GMT, TMT, and NOIRLab.

[The whole of section K3 is relevant – see appendix]