J. Astrophys. Astr. (2013) **34,** 97–120

The Thirty-Meter Telescope: Science and Instrumentation for a Next-Generation Observatory

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Received 15 March 2013; accepted 25 June 2013

Abstract. The Thirty-Meter Telescope international observatory will enable transformational observations over the full cosmic timeline all the way from the first luminous objects in the Universe to the planets and moons of our own solar system. To realize its full scientific potential, TMT will be equipped with a powerful suite of adaptive optics systems and science instruments. Three science instruments will be available at first light: an optical multi-object spectrometer, a near-infrared multi-slit spectrometer and a diffraction-limited near-infrared imager and integral field spectrometer. In addition to these three instruments, a diverse set of new instruments under study will bring additional workhorse capabilities to serve the science interests of a broad user community. The development of TMT instruments represents a large, long-term program that offers a wide range of opportunities to all TMT partners.

Key words. Telescopes—instrumentation: spectrographs—instrumentation: photometers.

1. Introduction

The Thirty-Meter Telescope (TMT) will be a flagship facility for addressing many compelling areas in astrophysics and delivering currently unforeseen discoveries in astronomy. TMT will lead a new generation of giant optical/infra-red, ground-based telescopes with fully integrated Adaptive Optics (AO). An overview of the TMT Observatory is given in Sanders (2013), and the TMT Adaptive Optics program is described in Ellerbroek (2013). This paper focuses on the science of TMT and its instruments. It is organized as follows: the science and the flow-down to requirements are described in Section 2, the first-light instruments are presented in Section 3, and the development of future instruments is discussed in Section 4.

2. TMT science

2.1 *Highlights of TMT's impact on the big science questions*

The large aperture size and field-of-view of TMT combined with its powerful adaptive optics systems and science instruments will provide unique gains in precision astrometry, high contrast imaging and spectroscopy from the ultraviolet through the mid-infrared to open new regions of discovery space on a number of 'big questions' reaching from the distant Universe to our own solar system.

2.1.1 *What is the nature and composition of the Universe?* The nature of dark matter and energy, the ingredients that dominate the composition of the Universe, remains a complete mystery. The lower limit of the dark matter mass spectrum depends on the nature of the dark particle ('warm' versus 'cold'). Diffraction-limited imaging with TMT of anomalies in strong gravitational lenses will probe this limit down to levels at least ten times smaller than currently possible. Different dark energy models predict different rates of evolution for cosmic distances and structures, and deep spectroscopy of very distant supernovae (up to $z = 4$) with TMT will provide a longer timeline over which these changes may be more readily detected.

2.1.2 *When did galaxies form and how did they evolve?* TMT can study galaxy formation both near and far. It will be able to detect the spectroscopic signatures of metal-free star formation, i.e., of the first stars forming in the first galaxies at redshifts well beyond 10. The sensitivity of TMT will overcome the 'photon starvation' plaguing the existing 8- to 10-m telescopes to produce detailed, spatially-resolved maps of morphology, chemistry and kinematics for galaxies out to $z = 5$–6 with a fidelity equivalent to what is currently done at $z < 1$. The large field-of-view and excellent UV throughput of TMT will enable powerful surveys of stellar abundances and ages in the halo of our own Milky Way over a volume nearly 100 times larger than previously possible to build a far more complete census of the smaller fragments that were hierarchically assembled into this halo. TMT will also be able to perform photometry of spatially-resolved stellar populations in galaxies out to the distance of the Virgo cluster to provide the first-ever 'archeological' sample large enough to unambiguously show the stochastic nature of galaxy assembly.

2.1.3 *What is the relationship between black holes and galaxies?* Black holes with masses as high as a billion times the mass of the Sun are now known to occupy the centers of galaxies. They warp space-time in fascinating ways, and their formation process is unknown, but it must be intimately linked to galaxy formation. If mass is the link, then the black hole mass function should track the galaxy mass function across the entire Hubble sequence and across time. The spatial resolution and sensitivity of TMT will make it possible to measure the black hole mass function down to masses ten times smaller and make dynamical measurements in galaxies more than 20 times farther than currently possible. TMT will expand by a factor of 1000 the number of galaxies where direct black hole mass measurements can be performed.

2.1.4 *How do stars and planets form?* The initial mass function of stars is the result of a competition between mass infall and outflows. The signatures of this competition can only be seen through diffraction-limited, high spectral resolution observations of obscured regions close to protostars in the mid-infrared, and TMT provides such a capability. TMT will obtain the first direct and definitive initial mass function measurements beyond our Galaxy. TMT will be able to make direct measurements of the masses of mature stars by imaging their astrometric microlensing effects at the milliarcsecond level. Morpho-kinematical mapping of proto-planetary disks with a spatial resolution five times greater than currently possible will unveil the gaps in which planets are forming.

2.1.5 *What is the nature of extra-solar planets?* Space missions like Kepler are producing an exciting crop of new exoplanets in addition to the ones already discovered through radial velocity monitoring, and the first exoplanetary system has also been imaged directly. All of these spectacular discoveries need to be followed up and characterized through high-contrast imaging and high-resolution spectroscopy. The higher spatial resolution and light gathering power of TMT will make it possible to distinguish rocky worlds from 'micro-Neptunes' and to search for brightness fluctuations caused by weather on giant exoplanets. TMT will even directly image mature, cold planets as small as Neptune by their reflected light at distances comparable to the size of the inner solar system, and the age-old question of how many planetary systems share the same architecture as our own solar system will be finally answered.

2.1.6 *Is there life elsewhere in the Universe?* Determining how and in what quantity pre-biotic molecules are deposited onto the surface of forming exoplanets is key to our understanding of the origin of life. High spatial resolution is needed to probe planet-forming disks at radial distances ($\sim$1 AU) where terrestrial planets are expected to form, and high spectral resolution in the mid-infrared is essential to search for these complex molecules. Transmission spectroscopy of exoplanet transits with TMT will yield the chemical composition of exo-planetary atmosphere with the possibility of detecting life through bio-markers such as oxygen.

2.2 *Towards defining the TMT science mission*

The TMT project was initiated in response to the 2001 National Academy of Sciences 'Decadal Survey' report *Astronomy and Astrophysics in the New Millennium* (AASC 2001), which ranked a Giant Segmented Mirror Telescope as the number one ground-based initiative. As envisaged by the Decadal Survey, TMT has pursued a public–private partnership as a key means to achieve this ambitious facility. Renewed support for a giant telescope was provided in the 2010 U.S. Decadal Survey report *New Worlds, New Horizons in Astronomy and Astrophysics* ('Astro2010' hereafter, AASC 2010). From 2004 to the present, TMT astronomers have developed detailed scientific plans for the observatory in full coordination with members of the broader U.S. astronomical community and new international partners. In addition, more than 200 scientists and engineers, at 44 institutions across North America and two in Europe, contributed to the TMT science case in the course of instrument feasibility studies.

TMT's science mission has also been developed in concert with that for other existing and proposed facilities. TMT astronomers participated actively in the important study *A Giant Segmented Mirror Telescope: Synergy with the James Webb Space Telescope* (Kudritzki *et al.* 2005) and provided key input into the Astro2010 process emphasizing the synergy with the Atacama Large Millimeter Array (ALMA) and the Large Synoptic Survey Telescope (LSST). As a result of these interactions, TMT's Detailed Science Case (DSC) (available from www.tmt.org) addresses 22 of the 24 science areas and 43 of the 68 'basic science questions' listed in the Astro2010 Decadal Survey report.

TMT follows a comprehensive system engineering process in every aspect. Foremost in this process is the careful flow down from TMT science and science-based requirements, to design requirements of every TMT subsystem and to the integrated TMT system. The development of detailed science cases for TMT led to the formulation of the top-level requirements on the observatory design (see Section 2.3). These top-level requirements have been flowed down to lower level detailed requirements on the system.

The science advances offered by TMT are made possible through the groundwork of years of experience within the TMT partner communities; development of a unique combination of advanced technologies, innovative design and systems engineering. The key observatory design choices include:

- A 30-m diameter, filled-aperture pupil maximizing near-diffraction-limited performance, contrast, and uniform point spread function.
- Steerable tertiary mirror to address multiple instruments quickly, increasing observational efficiency, and enabling key science cases involving rapid follow-up of targets of opportunity and transient objects.
- An adaptive optics system that will provide a *unique first-light* combination of diffraction limited correction in J, H and K bands, a large and astrophysically useful field, excellent image uniformity and stability, and extensive sky coverage (greater than 50 per cent at the galactic pole).
- Telescope and instrument designs with minimal optical elements and cooled instrument environments providing low throughput losses and low thermal background.
- A suite of highly efficient and stable instruments (see Section 2.4) addressing not only the DSC, but providing broad capabilities to support unforeseen science that will be enabled by TMT.

2.3 *Science flowdown to requirements*

How do we know that the current technical requirements and architecture for the TMT observatory will indeed allow TMT to tackle the broad range science within the reach of a large optical/IR telescope and fully realize its scientific potential? The path from science to observatory design is not necessarily linear, and it may involve multiple iterations. Nonetheless, the final design must meet as many science requirements as possible within the constraints imposed by technological readiness, schedule and cost. A properly established science flowdown plays an essential role in estimating and optimizing the impact of various design decisions to maximize science returns.

A schematic diagram of the TMT science flowdown (Simard and Crampton 2010) is shown in Fig. 1. The first step was taken in 2000–2004 when a set of initial science cases was written for TMT. These science cases helped define a set of instrument capabilities organized according to fundamental observational parameters such as wavelength range, spectral and spatial resolution, and field-of-view. These capabilities were packaged into a desired suite of AO systems and instruments, and requirements for this suite were captured in the initial version of the Science-based Requirements Document (SRD) (available from www.tmt.org).

Science cases and operational concepts from the instrument feasibility studies were used to write the TMT DSC. The DSC describes forty-three science programs that span a wide range of science explorations. More than 230 requirements were derived from these science programs and captured in a revised version of the SRD. The links between science cases and the SRD have been established in the TMT Science Flowdown Matrix that uses twenty observing parameters to characterize the TMT science programs. Table 1 is a very high level summary distilled from the above three elements of the TMT science flowdown (full matrix has 54 rows and 31 columns), and Table 2 gives more details on the instrument capabilities derived from this flowdown. TMT's versatile design delivers capabilities that strongly overlap with the science objectives of Astro2010.

All science programs developed so far for TMT (and other extremely large telescopes) should be taken as exemplars since much of the legacy of TMT cannot be

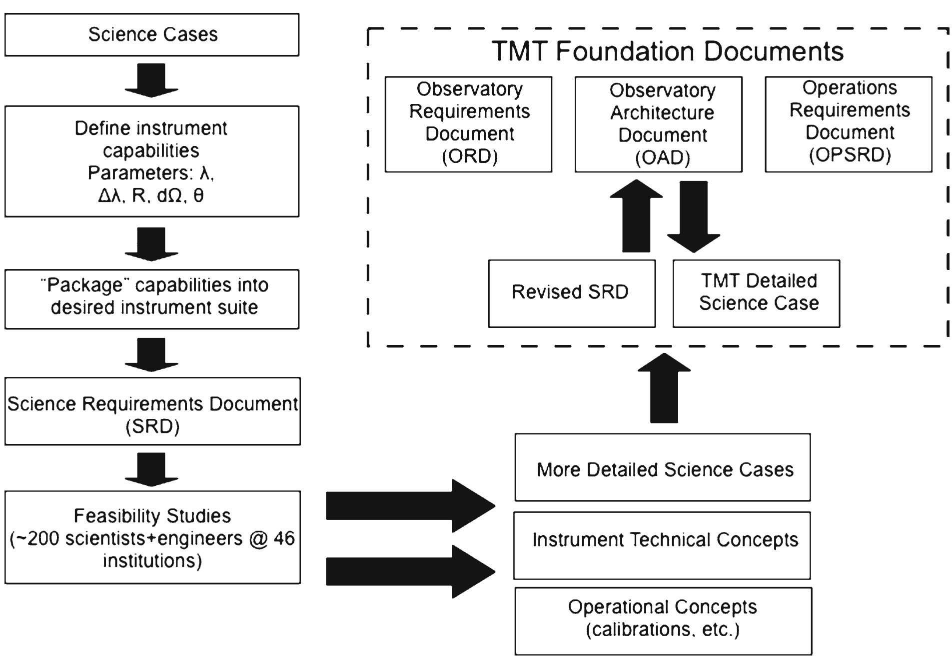

Figure 1. Schematic diagram of the TMT science flowdown

Table 1. TMT science objectives and capabilities and their links to the 2010 US Decadal Survey Science. These links are Cosmology and Fundamental Physics (CFP), Galactic Neighborhood (GAN), Galaxies Across Time (GCT), Planetary Systems and Star Formation (PSF) and Stars and Stellar Evolution (SSE) (AASC 2010). The symbol '◆' denotes first-light science.

Theme	Science objectives	Observations	Requirements	Capabilities
Cosmology and fundamental physics (dark energy, dark matter, physics of extreme objects, fundamental constants; DSC Section 3)	Mapping distribution of dark matter on large and small scales (CFP-[1,2,3,4], GAN-[3,4], GCT-1) General relativity in new mass regime◆ (GAN-[4,D], SSE-4) Very precise expansion rate of Universe (CFP-2) Mapping variations in constants over cosmological timescales Physics of extreme objects◆ (SSE-[2,3,D])	Proper motions in dwarf galaxies Wide-field optical spectroscopy of $R = 24.5$ galaxies Microarcsecond astrometry Transient events lasting >30 days High spectral resolution observations of quasars and GRBs	$\lambda = 0.31$–0.62 µm, 2–2.4 µm $R = 1000$–50000 Very efficient acquisition 0.05 mas astrometry stable over 10 years Field-of-view $>10'$	SL/WFOS SL/HROS MCAO/IRIS/WIRC MCAO/NIRES
The early Universe (first objects, IGM at $z > 7$; DSC Section 4)	Detection of metal-free star formation in First Light objects◆ (GAN-2, GCT-4) Mapping topology of re-ionization (GCT-4) Structure and neutral fraction of IGM at $z > 7$ (CFP-1, GCT-4)	Multiplexed, spatially-resolved spectroscopy of faint objects High spectral resolution, near-IR spectroscopy	$\lambda = 0.8$–2.5 µm $R = 3000$–30000 $F = 3 \times 10$–20 ergs $s^{-1}cm^{-2}Å^{-1}$ Exposure times >15 ks	MCAO/IRMS/IRIS MOAO/IRMOS MCAO/NIRES
Galaxy formation and the IGM (DSC Section 5)	Baryons at epoch of peak galaxy formation◆ (CFP-1, GAN-1, GCT-[1,2]) 2D Velocity, SFR, extinction & metallicity maps of galaxies at $z = 5$–6◆ (CFP-3, GAN-1, GCT-[1,2])	Optical/near-IR multiplexed diagnostic spectroscopy of distant galaxies & AGNs Optical/near-IR multiplexed identification spectroscopy of extremely faint high redshift objects (to R–27)	$\lambda = 0.31 - 2.5$ µm $R = 3000$–5000, 50000 Very efficient acquisition Multiplexing factor >100	SL/WFOS SL/HROS MCAO/IRIS/IRMS MOAO/IRMOS

Table 1. (*continued*)

Theme	Science Objectives	Observations	Requirements	Capabilities
	IGM properties on physical scales <300 kpc◆ (GAN-1, GCT-2)	Spatially-resolved spectroscopy		
Extragalactic supermassive black holes (DSC Section 6)	Demographics of black holes over new ranges in mass and redshift◆ (GAN-4, GCT-3) Dynamical measurements out to $z = 0.4$◆ (GAN-4,GCT-[1,3]) Scaling relations out to $z = 2.5$ and masses at $z > 6$◆ (GAN-4, GCT-[1,3])	Spatially-resolved spectroscopy of galaxy cores	$\lambda = 0.8$–2.5 μm $R = 3000$–5000 Precise positioning	MCAO/IRIS MOAO/IRMOS
Galactic neighborhood (DSC Section 7)	Abundance of oldest stars in Milky Way (CFP-4, GAN-[2,3], SSE-2) Chemical evolution in local group galaxies◆ (GAN-2) Diffusion and mass loss in stars (GAN-1, SSE-1) Resolved stellar populations out to Virgo cluster◆ (GAN-[2,3])	High spectral resolution optical and near-IR spectroscopy High-precision photometry in crowded fields	$\lambda = 0.33$–0.9, 1.4–2.4 μm $R = 4{,}000$, $40{,}000$–$90{,}000$ Photometry precision of 0.03 mag at Strehl $= 0.6$	SL/HROS MCAO/NIRES MCAO/IRIS/WIRC SL/WFOS

Table 1. (*continued*)

Theme	Science Objectives	Observations	Requirements	Capabilities
Planetary systems and star formation (physics of star formation, proto-planetary disks, exoplanets; DSC Section 8, Section 9)	Origin of mass in stars (GAN-[1,2], PSF-1) Architecture of planetary systems (PSF-[2,3,D]) Deposition of pre-biotic molecules onto protoplanetary surfaces (PSF-2)	High-precision, crowded field photometry Diffraction-limited, high spectral resolution mid-IR spectroscopy Very high Strehl AO-assisted imaging: precise wavefront control	$\lambda = 1$–25 μm $R = 4000$, 30000–100000 Low telescope emissivity Dry site (PWV < 5 mm) Fixed gravity vector and thermal control	MCAO/IRIS MIRAO/MIRES MCAO/NIRES SL/HROS ExAO/PFI
	First direct detection of reflected-light Jovians (PSF-2) Characterization of exo-atmospheres (e.g., oxygen) (PSF-[3,4,D])	High spectral resolution optical and near-IR spectroscopy	Very efficient acquisition Contrast ratio of 10^8–10^9	
Our solar system (outer parts, surface physics and atmospheres; (DSC Section 10)	Composition of Kuiper Belt Objects and comets (PSF-2) Monitoring weather, (cryo-) vulcanism and tectonic activity◆	Spatially resolved spectroscopy of objects in solar system Transient events (hours to years)	$\lambda = 1$–10 μm $R = 1000$–100000 Non-sidereal tracking Fast response time	MCAO/IRIS/WIRC MCAO/NIRES MIRAO/MIRES

Table 2. Instrument capabilities currently planned for TMT. The first three are first-light instruments.

Instrument	Field of view/slit length	Spectral resolution	λ (μm)	Comments
InfraRed Imager and Spectrometer (IRIS)	< 4.″4 × 2″.25 (IFU) 16″.4″ × 16″.4″ (imaging)	4000–8000 5–100 (imaging)	0.8–2.4	MCAO with NFIRAOS
Wide-Field Optical spectrometer (WFOS)	40.3′ squared (F0V) 576″ (total slit length)	1000–8000	0.31–1.1	Seeing-Limited (SL)
InfraRed Multislit Spectrometer (IRMS)	2′ field w/46 deployable slits	$R = 4660$ @ 0.16″ slit	0.95–2.45	MCAO with NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	3″ IFUs over >5′ diameter field	2000–10000	0.8–2.5	MOAO
Mid-IR AC-fed Echelle Spectrometer (MIRES)	3″ slit length 10″ imaging	5000–100000	8–18 4.5–28 (goal)	MIRAO
Planet Formation Instrument (PFI)	1″ outer working angle, 0.05″ inner working angle	$R \leq 100$	1–2.5 1–5 (goal)	10^8 contrast 10^9 goal
Near-IR AO-fed Echelle Spectrometer (NIRES)	2″ slit length	20000–100000	1–5	MCAO with NFIRAOS
High-Resolution Optical Spectrometer (HROS)	5″ slit length	50000	0.31–1.0 0.31–1.3 (goal)	SL
"Wide"-field AC imager (WIRC)	30″ imaging field	5–100	0.8–5.0 0.6–5.0 (goal)	MCAO with NFIRAOS

foretold. Maximizing the discovery potential of the observatory through the availability of flexible workhorse capabilities is therefore a prime design driver. To illustrate how Table 1 works, we focus on two very different themes and indicate how the table can be used to generate the flowdown to technical requirements.

2.3.1 *Origin of stars, planets and life.* What determines the mass of a star? Are planetary systems like our own, with the potential for life, common or rare? How and when are planetary systems formed? How might life arise in these systems? Are the organic precursor molecules for life common in planet-forming disks?

The first key capability is diffraction-limited, high-resolution spectroscopy in the near- and mid-infrared (MCAO/NIRES and MIRAO/MIRES). The mass of a star is the result of a competition between infall and outflows. The spatial resolution of TMT will be uniquely capable of probing the very inner region of disks where outflows are launched. This spatial resolution will also allow TMT to map the distribution of complex, molecular species associated with life at radii of a few astronomical units from the protostar where terrestrial planets are expected to be found (Lahuis *et al.* 2006; Markwich *et al.* 2002). High-resolution spectroscopy will allow robust identification of these species. Detailed line velocity profiles will also be used to determine the structure of gaps in disks where exoplanets may be forming. Mid-infrared observations require a high altitude and dry site to minimize pressure broadening of the atmospheric absorption lines and maximize atmospheric transparency (Precipitable Water Vapor (PWV) < 1 mm at least 10 per cent of the time).

The second capability is high contrast imaging with extreme adaptive optics and the Planet Formation Instrument (ExAO/PFI). In order to directly image Jupiter-like exoplanets in reflected light, a contrast ratio of 10^8 within inner/outer working angles of $0''.05$ and $1''$ is required. This can only be achieved with an aperture of at least 30 m, a clean point-spread-function, exquisite wavefront control, and stringent requirements on mirror segment surface errors and cleanliness. Another objective is the first direct detection of jovian planets in the Taurus star-formation region at a distance of 140 parsecs. The required contrast level for observing jovian planets in this unique environment is 10^6 at $0''.03$ from the star. This is firmly into TMT-only discovery space and will place our solar system in context and establish the frequency of planets including those in the ‘habitable zone.’

Spatially resolved (as fine as $\sim$25 km at the distance of Jupiter) time domain observations of the atmospheres and surface features of planets, satellites, asteroids and trans-Neptunian objects with MCAO/IRIS promise to reveal the physics and chemistry of our own solar system, including the potential identification of pre-biotic molecules. Requirements on observing efficiency with TMT including short acquisition time, minimum downtime and quick response time will enable the monitoring of weather, volcanism and tectonic activity over appropriate timelines.

2.3.2 *Galaxy formation.* Why do stars in the largest galaxies appear to form first yet dark matter halos form hierarchically? Is star formation different at high z and how is it regulated? How do galaxies acquire gas from and return metals to the intergalactic medium? What are the effects of supernovae and AGN feedback on galaxy properties? Photon starvation precludes the requisite studies to answer these questions with current facilities, but TMT with Multi-Conjugate and Multi-Object AO (MCAO/IRIS and MOAO/IRMOS) will be able to spatially dissect galaxies to produce detailed velocity, extinction, star formation and metallicity maps of galaxies out to $z \sim 5$ with a level of fidelity comparable to what is available for the nearby Universe. Large samples with a spatial sampling of 50 mas over arcminute-scale fields are needed for this project to properly measure fundamental quantities such as angular momentum. High-order AO corrections over small patches as provided by MOAO coupled to a system of multiple, deployable IFUs (IRMOS) is the ideal capability.

Multi-object, wide-field, seeing-limited optical spectroscopy (SL/WFOS) will go $\sim$2.5 magnitudes deeper than 8–10 m class telescopes, and background UV-bright galaxies will then become usable beacons to study the distribution of neutral hydrogen in the IGM; the surface density of sightlines on the sky for IGM tomography will be $\sim$200 times higher for a given cosmological volume. This means that one will be able to probe individual galaxy haloes through multiple sightlines and derive the complete picture: the relative distribution of gas, dark matter and galaxies. TMT is a wide-field telescope (a key requirement here) when applied to the high redshift Universe with its 20 arcminute field being equivalent to 3.4° at low redshifts comparable to the Sloan Digital Sky Survey.

It will also be possible to conduct 'galaxy archaeology' using resolved stellar populations. Detailed color-magnitude diagrams for galaxies out to the distance of the Virgo cluster will allow us to reconstruct how they formed through hierarchical assembly. The intricacies of this stochastic process can only be studied with a truly representative sample of galaxy types, something not possible locally. TMT will be able to produce a deep-color magnitude diagram for a normal elliptical galaxy. Milliarcsecond-resolution images with Strehl ratios above 0.5 and photometric precision of 0.03 mag are required with MCAO/IRIS/WIRC to reach these objectives.

It is not easy to visualize the mappings between science programs and requirements because they are inherently multi-dimensional. These have been performed rigorously through deconstructing the DSC document, and requirement traceability. However, the overlap between science and requirements can still be shown through some simple, two-dimensional projections. Figure 2 shows science programs and instrument capabilities projected onto spatial and spectral resolution. This particular projection is interesting because extremely large telescopes are expected to open new regions in this discovery space with assistance from adaptive optics. As this figure shows, the planned TMT-enabled instrument capabilities overlap very nicely with its proposed science programs.

2.4 *Science instrument capabilities*

The initial SRD guided the phase of instrument feasibility studies conducted in 2005 and 2006. Science and technical teams involving a total of about 200 scientists and engineers from 46 different institutions in North America and Europe participated in ten feasibility studies of eight instrument concepts that make up the TMT planned instrument suite (Table 2, WIRC was not studied as part of this phase). In addition to establishing the feasibility of instrument designs, these studies produced two very

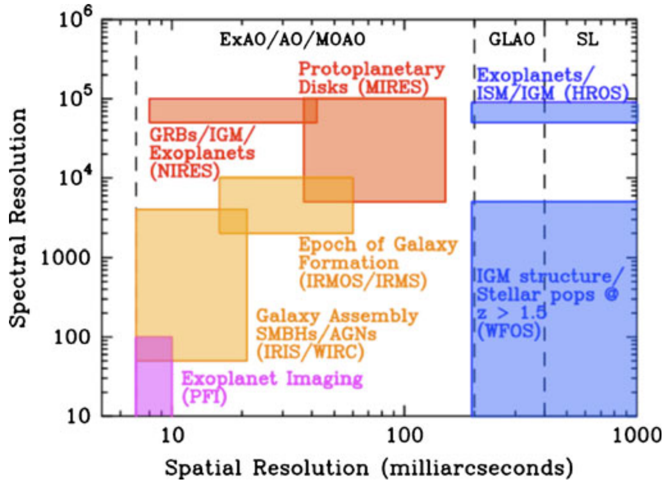

Figure 2. Science programs and TMT-enabled instrumentation capabilities in spectral versus spatial resolution discovery space. Colors represent wavelength ranges from optical (blue) to mid-infrared (red)

important deliverables: (1) more detailed science cases and (2) full observing programs in the form of well-defined operational concepts. As an example, the science cases from the two competing IRMOS feasibility studies covered tens of pages and included detailed simulations of the velocity fields of very distant galaxies. Observing programs were described in sufficient details to subsequently study some very practical implications such as calibration systems, object selection for multi-object spectroscopy and efficient acquisition scenarios just to name a few.

2.5 *Synergy with other facilities*

The synergy between the next generation of large facilities has already received a lot of attention in the community, and many meetings have been devoted to linking science cases across different wavelengths. Past synergies (e.g., HST and the 8–10 m telescopes) are a template for the future with even more powerful facilities. The synergy of TMT with other facilities falls into three main categories: (1) spectroscopic characterization of interesting objects found in wide-field surveys, (2) rapid follow-up to fully realize the discovery potential of time-domain astronomy and (3) multi-wavelength mapping at high spatial resolution of targets rich in detailed substructures.

Many future space-based and ground-based facilities aim to conduct wide-field surveys. GAIA will launch in 2013 on a five plus-year astrometric mission. It will provide TMT with an all-sky astrometric reference frame with sub-milliarcsecond quality down to $V = 20$. It will screen all stars within 200 parsecs for Jupiter-sized planets and deliver a target list to directly image nearby planetary systems. It will also identify candidate ‘first stars’ in the Milky Way suitable for nucleocosmochronometry. The Euclid space telescope to be launched in 2020 will image 15,000 square degrees in the optical/near-IR and uncover supernovae and gravitational lenses that will require detailed follow-up. HyperSuprimeCam and LSST will also discover thousands of exotic objects such as gravitational lenses that will require high resolution imaging follow-up (Treu 2010). Only TMT will have the resolution and speed to achieve this goal.

The Square Kilometer Array (SKA) will survey the three-dimensional distribution of neutral hydrogen during the 'Dark Ages' over wide swaths of the sky with a field-of-view of one square degree and a spatial resolution less than $0''.1$. TMT will observe the first luminous objects to emerge from these Dark Ages on similar resolution scales. SKA will also survey sources at the microjansky and nanojansky levels (Padovani 2011), and these sources are expected to be so optically faint that TMT will be required for spectroscopic follow-ups. It will then be possible with TMT and SKA to study star formation rates and feedback from active galactic nuclei in *normal* galaxies out to $z = 6$. JWST and TMT will be another powerful combination for the study of the first stars and the first galaxies. The field-of-view ($3'$) and the sensitivity of JWST out to mid-infrared wavelengths will be ideal for detecting those very distant objects that are also expected to be very small (sizes ≤ 80 mas to 100 mas with redshifts $z > 10$–20). Multi-slit spectroscopy on TMT is the key for determining mass/kinematics, metallicity, outflows and the initial mass function of these distant objects. The diffraction-limited image size provided by TMT is a good match to the size of a HII region at these redshifts. Even an extremely large telescope will not reach down to the level of the continuum, and TMT observations will be complemented by spectral energy distributions from JWST broadband imaging to secure equivalent line widths. Deployable, AO-assisted IFUs on TMT will also be able to map large ionized bubbles around JWST sources to characterize the topology of re-ionization. With its capability to image dust continuum to a redshift of $z = 10$, ALMA will provide complementary information about the content of JWST/TMT sources for a full baryonic inventory.

As shown in Fig. 3, ALMA and TMT have the same (high) spatial resolution. High resolution is clearly essential for mapping targets rich in detailed structures such as protoplanetary disks, and different wavelengths probe different physical regimes in an integrated way. For example, ALMA will study the outer, colder regions of protoplanetary disks while TMT will provide a direct look at the inner (less than a few astronomical units), warmer regions where terrestrial and giant planets form. ALMA will also reveal the tidal gaps created by protoplanets, and TMT will image these protoplanets themselves through high-contrast imaging. The sensitivity of TMT/MIRES to an unresolved spectral line is comparable to JWST/MIRI but with spectral resolution (Fig. 3) sufficient to understand the underlying physics. Spectra of gaseous lines with TMT will provide critical velocity information to understand the radial location of the gas, and how the dynamical/chemical/physical structure of these disks will evolve with time.

Time-domain astronomy (e.g., Pan-STARRS, HyperSuprimeCam, LSST, gamma and X-ray space missions) holds significant discovery potential, and very wide-field synoptic surveys are expected to produce very large numbers of transient detections that require rapid follow-up. Most of the discovery space for cosmic transients (the "Unknown Unknowns") actually lies in the domain of very fast (2 minutes $\leq$ decay time $\leq$ 2 hours) transients (Abell *et al.* 2009). One of the LSST mini-surveys will cover a small number of 10 square degree fields every $\sim$15 seconds for about an

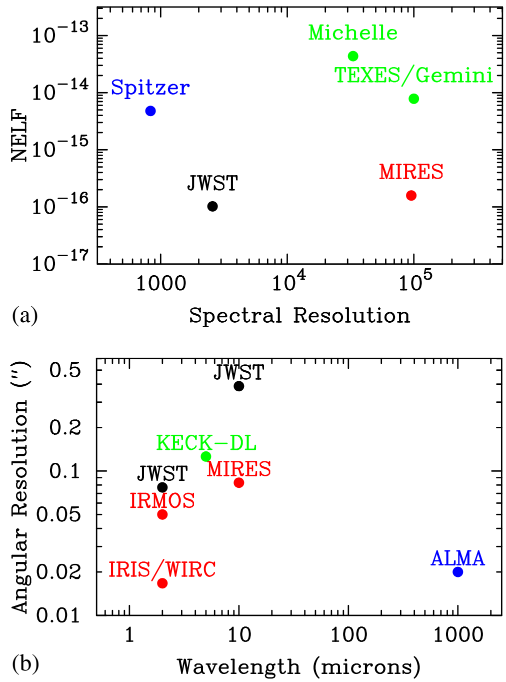

Figure 3. TMT instrument capabilities (in red) compared to JWST and ALMA. (**a**) TMT/MIRES will have comparable spectral line sensitivity to infrared space missions but with a much higher spectral resolution. NELF is the Noise-Equivalent Line Flux in ergs s^{-1} cm^{-2}; (**b**) The angular resolutions of TMT instruments nicely complement that of JWST and ALMA. TMT and ALMA will have comparable angular resolutions at completely different wavelengths. Down is better in both panels.

hour out of every night to catch some of these very fast transients. To be able to observe a vast array of transient events, TMT is being designed as a rapid response system with stringent requirements for short slew and acquisition times, and short configuration times for its active and adaptive optics systems. TMT will be ready to observe the next target with the same instrument within five minutes and switch to any instrument in less than 10 minutes, and it will therefore fall squarely in the time regime required to follow up new types of exotic transients.

3. First-light science instruments

3.1 *Selection process*

Technical designs and operational concepts developed in 2005 and 2006 as part of the feasibility studies of the instrument capabilities listed in Table 2 provided the opportunity to explore the potential of TMT equipped with realistic instruments, and to verify and expand on the overall observatory requirements. After reviewing the instrument concepts, capabilities and costs, the suite of science instruments was divided by the TMT Science Advisory Committee (SAC) in December 2006 into 'first light' and 'future' instruments. This selection was based on scientific priority and synergies with James Webb Space Telescope (JWST) and Atacama Large Millimeter Array (ALMA) as well as a variety of pragmatic reasons including cost constraints, commissioning practicalities, and technological readiness. The first-light instruments are part of the TMT construction budget, and the remaining instruments will be developed, built and commissioned under the guidance of an instrumentation development office. All instruments will be delivered with data reduction modules that can be used for quick-look pipelines and optimized by users to produce science-ready, processed data according to their specific science applications. More information on the proposed suite of TMT instruments is given in the TMT Instrumentation and Performance Handbook (available from www.tmt.org).

3.2 *InfraRed imaging spectrometer (IRIS)*

IRIS is an integral field spectrometer and imager designed to work with the NFIRAOS multi-conjugate Adaptive Optics (AO) system (Herriot *et al.* 2010, 2012; Ellerbroek *et al.* 2012; Ellerbroek 2013) over the 0.84 to 2.4 μm wavelength range (Larkin *et al.* 2010; Moore *et al.* 2010; Barton *et al.* 2010; Simard *et al.* 2012). It will thus provide diffraction-limited imaging for precision photometry and astrometry over a sizable, uniform field ($17'' \times 17''$) and integral field spectroscopy with spectral resolutions of at least $R > 3500$ at various spatial scales ($0''.004$, $0''.010$, $0''.025$ and $0''.050$ per pixel). IRIS is optimized to exploit the full potential of a 30-m telescope for precision imaging and spectroscopy at high spatial resolution and very faint limits, capitalizing on the D^4 gain for point-like sources in the diffraction-limited regime. To achieve these goals, IRIS includes a set of three near-infrared wavefront sensors that can be precisely positioned and locked onto AO-sharpened natural guide stars to control focus, astigmatism and tilt anisoplanatism for NFIRAOS (blind modes in a Laser Guide Star system). The natural guide stars can be selected over a 2-minute field, providing better than 50 per cent sky coverage with less than 2 mas of jitter, even at the galactic poles. Astrometric accuracies of better than 50 μas in short, 100-second exposures will be achievable over the entire field of the imager. The imager will deliver images with total residual wavefront errors of less than 30 nm.

An innovative 'hybrid' design is used by the IRIS spectrometer to achieve integral field spectroscopy with both the highest possible image quality (using a lenslet array) and the highest possible sensitivity (using an image slicer). The lenslet integral field system will deliver spectra of objects with either 4 mas or 10 mas spatial sampling and a 5 per cent spectral band pass; the image slicer spectrometer will deliver spatial sampling of either 25 mas or 50 mas over areas up to $2''.2$ by $4''.4$ in size, covering full near-infrared bands. Higher spectral resolutions (up to $R = 10{,}000$) are achievable with more limited wavelength coverage. Only the image dissection technique changes in the spectrometer: most of the foreoptics, camera optics and detector are common, significantly reducing cost and risk.

The following organizations are involved in the IRIS science and technical teams: Caltech, UC (Los Angeles, Irvine, Santa Cruz, Berkeley), Herzberg Institute of Astrophysics, and National Astronomical Observatory of Japan. The co-PIs are James Larkin (UCLA) and Anna Moore (Caltech). The project scientist is Shelley

Wright (U. Toronto). Ryuji Suzuki (NAOJ) is leading the design of the imager. The IRIS design greatly benefits from the legacy of Keck/OSIRIS, Keck/MOSFIRE and Gemini/GPI instruments. A feasibility study was completed and externally reviewed in March 2006. A conceptual design study was completed and reviewed in December 2011. Prototypes for the wavefront sensor probe arms, the spectrograph grating turret and the atmospheric dispersion compensator glass have been built and tested in 2012. The preliminary design phase started in March 2013.

Figure 4 shows an exploded view of the full IRIS assembly. More details on IRIS are given on the IRIS website (http://irlab.astro.ucla.edu).

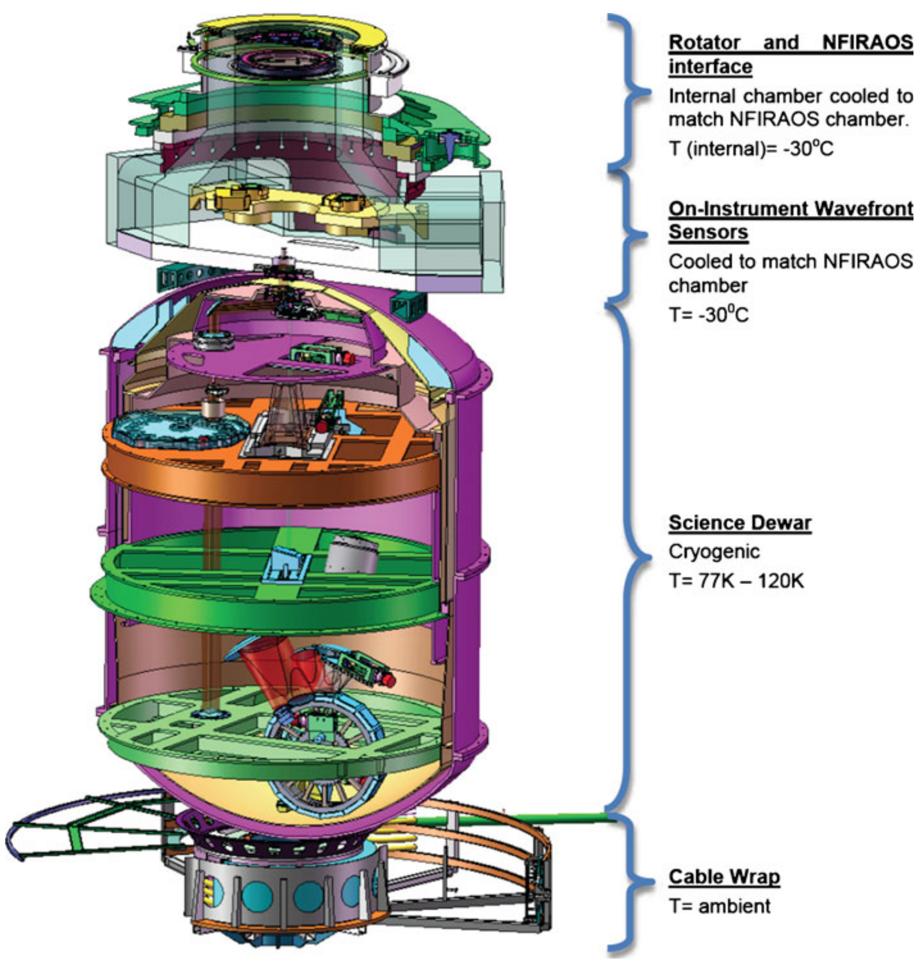

Figure 4. Cut-away of the IRIS instrument assembly showing the major instrument subassemblies. Only the vacuum-sealed science dewar is maintained at cryogenic temperatures. The remaining modules are cooled to $-30°C$, which is the NFIRAOS enclosure temperature. The science dewar contains the IRIS imager and the integral field spectroscopic channels.

3.3 *Multi-Object Broadband Imaging Echellette (MOBIE)*

The fundamental science parameters of a spectrograph are field-of-view, total slit length, spectral resolution and simultaneous wavelength coverage. There is a tension between these parameters depending on the types of spectroscopy programs that will be carried out. 'Survey spectroscopy' (e.g., redshift determination) needs to achieve high multiplexing factors by maximizing both field-of-view and total slit length. 'Diagnostic spectroscopy' (e.g., chemical abundances through line ratios) requires wide wavelength coverage to simultaneously measure multiple lines and control systematics and relatively high spectral resolution to separate out line blends. Reconciling both types of spectroscopy within a single instrument is quite challenging. The latest design for TMT's Wide-Field Optical Spectrograph (WFOS) is the Multi-Object Broad-band Imaging Echellelette (MOBIE) spectrograph (Bernstein and Bigelow 2008; Bigelow and Bernstein 2010; Ellis *et al.* 2010; Simard *et al.* 2012), and it provides an elegant solution to that challenge. It can trade multiplexing for expanded wavelength coverage in its higher dispersion with the proper selection of a combination of grating, cross-dispersing prism and order-sorting filter. MOBIE's wavelength range is 0.31–1.1 μm with throughput higher than 40% at all wavelengths. The blue sensitivity of MOBIE was deemed to be of high scientific importance in probing important metal transitions in the intergalactic medium at all redshifts and in observations of extremely metal-poor stars. With its total field-of-view of 40 square arcminutes, and its total slit length of 576 arcseconds, MOBIE can observe as many as 200 objects simultaneously at low spectral resolution. The current design offers spectral resolutions of $R = 1000$, 5000 and 8000 for a $0''.75$ slit width. Achieving higher resolutions will be possible with narrower slits especially for point source observations. Figure 5 shows a schematic view of the current MOBIE design.

MOBIE is a collaboration between the University of California at Santa Cruz (UCSC), the California Institute of Technology (CIT), the Nanjing Institute of Astronomical Optics and Technology (NIAOT), the University of Science and Technology of China (USTC), the National Astronomical Observatory of Japan (NAOJ), and the University of Hawaii (UH). The principal investigator is Rebecca Bernstein (UCSC), the project manager is Bruce Bigelow (UCSC), and the project scientist is Charles Steidel (CIT). NIAOT/USTC are responsible for the design of the Acquisition, Guiding and Wavefront-Sensing (AGWFS) camera. NAOJ is working on the opto-mechanics of the blue and red spectrograph cameras, and UH is developing the instrument software requirements and architecture and designing the detector readout electronics. Many commercial vendors are also involved in various subsystem studies. MOBIE is currently halfway through its Conceptual Design Phase (CDP) with a review scheduled for October 2013. This phase includes producing optical and mechanical designs for all subsystems, defining electronics/software requirements/interfaces and updating cost and schedule estimates. Science activities include revised science cases and operational concepts, a data simulator and exposure time calculator as well as requirements for data reduction pipelines for imaging and spectroscopic modes. MOBIE requires relatively large optical elements, and single-point diamond turning of aspheric surfaces on a large (diameter ∼350 mm) piece of calcium fluoride is also being prototyped in this stage.

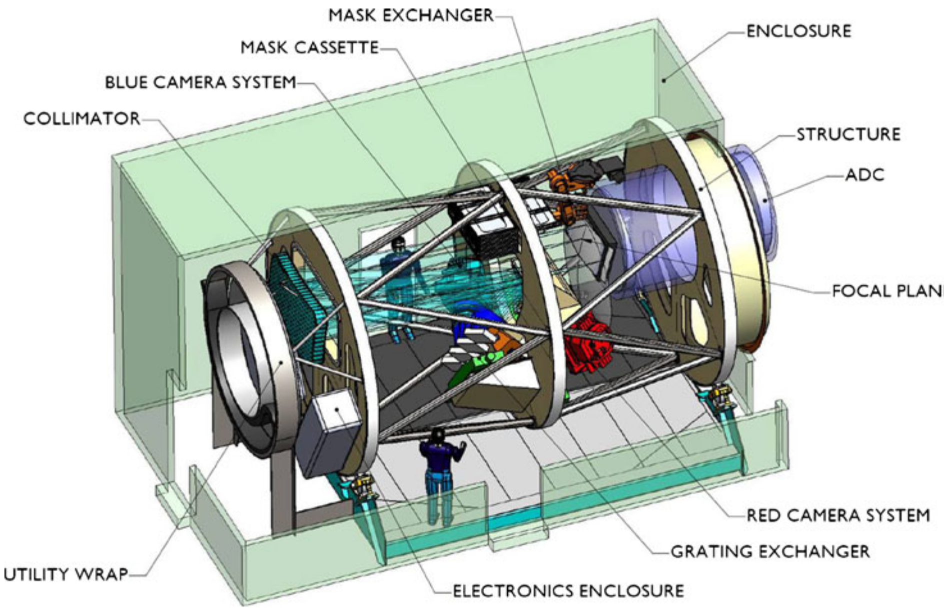

Figure 5. Schematic view of MOBIE (Courtesy: Bruce Bigelow, UCO/Lick). The cylindrical instrument assembly is four meters in diameter.

3.4 *InfraRed Multi-Slit Spectrometer (IRMS)*

Some form of multi-object, near-infrared spectroscopy is another essential capability for first light. Understanding the so-called 'First Light' objects in the Universe, the origin and evolution of galaxies and other objects detected by JWST and ALMA will require spectra of many extremely faint objects in the near-infrared, and multiplexing will thus be essential. Although the Science Advisory Committee (SAC) originally advocated a fully multiplexed deployable IFU system using Multiple Object AO (MOAO), this was deemed to be too risky and expensive for a first light instrument. Fortuitously a modified version of the MOSFIRE multi-slit instrument, recently installed on Keck (McLean *et al.* 2010, 2012), provides a very exciting interim capability. Although MOSFIRE is a seeing-limited instrument for Keck, it can be adapted for use in an AO mode with NFIRAOS, thus providing an exceedingly powerful capability for TMT at low risk and modest cost (Mobasher *et al.* 2010; Simard *et al.* 2012). When optimized for wide-field mode, NFIRAOS will deliver images to IRMS that will produce almost an order of magnitude gain in encircled energy within narrow (160 mas) slits over the entire of $2'$ diameter field. NFIRAOS plus IRMS is expected to deliver a K-band encircled energy within a radius of 80 mas six times higher than for seeing-limited observations.

MOSFIRE is a multi-slit instrument designed for the $f/15$ Cassegrain focus on the Keck 1 telescope (More details on the MOSFIRE project can be found at http://www.astro.ucla.edu/~irlab/mosfire/). This is the same f/ratio as for the output port of NFIRAOS and, without change to the MOSFIRE design, it would naturally take in the entirety of the NFIRAOS field of regard of $2'$ in diameter. It covers the wavelength range 0.95 μm to 2.45 μm with spectral resolution of up to $R = 4660$ for a $0''.16$ slit.

MOSFIRE uses a cryogenic slit mask unit (CSU) that was originally developed as a backup for the JWST NIRSPEC instrument (Spanoudakis *et al.* 2008). The spatial pixel scale (50 mas) on TMT and the length of individual slitlets in IRMS (made by masking bars in MOSFIRE) is reasonably well matched to the sampling scale requested in the TMT Science Requirements Document. For multiplexing, the individual bars can be configured up to 46 slitlets over the entire NFIRAOS field; in practice, some of the slitlets would be made into contiguous slits of lengths that are multiples of $2''.4$. The width of slits and their placement within the field are remotely configurable in real time.

IRMS on TMT will also offer additional capabilities. It can be configured as a long slit spectrograph or as an imager that would cover the entire NFIRAOS field of regard, albeit with spatial sampling of only 33 mas to 60 mas (roughly two to four times larger than the diffraction limit at 2 μm). It can also be used in a seeing-limited mode (for either imaging or spectroscopy), if desired, by flattening the deformable mirrors in NFIRAOS and turning off the AO correction. The MOSFIRE team at Caltech has recently completed a conceptual 'mini-study' for IRMS, and this study showed that the MOSFIRE design could indeed be modified to work with the TMT NFIRAOS system.

3.5 *A world map of the TMT instrument efforts*

The TMT instrument collaborations have evolved significantly over the last few years to encompass all partners. Figure 6 shows all the contributions from around the world to the science instrument efforts. In addition to the work underway on the three first-

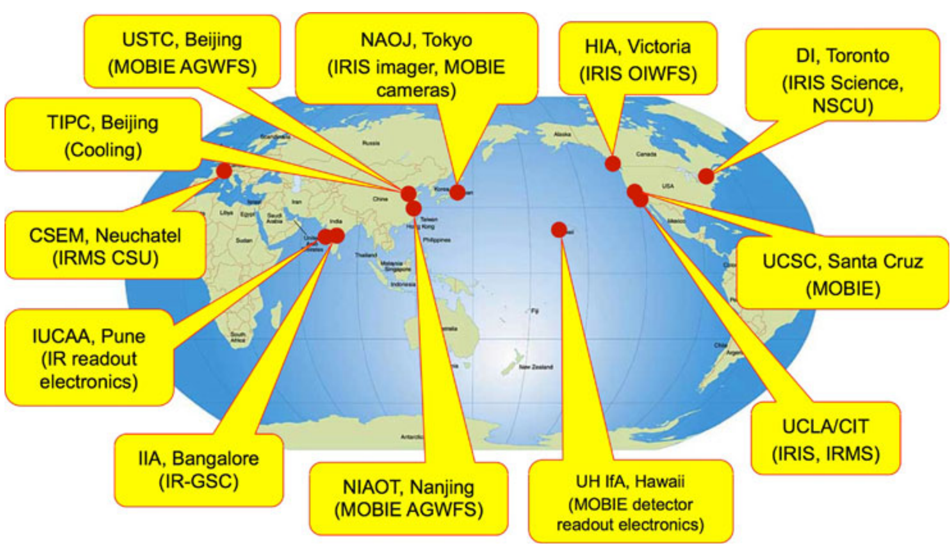

Figure 6. Contributions to the TMT science instrument effort from around the world.

light instruments, there is work in other instrument-related areas. TMT will require natural guide stars to provide tip-tilt-focus wavefront sensor measurements to its AO systems. As an example, NFIRAOS will require three natural guide stars with J-band, Vega-based magnitudes as faint as 22 over its $2'$ corrected field-of-view to achieve a sky coverage of at least 50% at the galactic poles. Currently, there is no all-sky, near-infrared survey down to this depth, and, based on planned surveys, there will likely still be no such survey by the time of TMT's first light in 2021. However, there should be extensive optical imaging available. Subramanian *et al.* (2013) is studying the possibility of generating infrared magnitude estimates and discriminating stars from galaxies using seeing-limited, multi-band, optical imaging. First results already look promising. Another interesting area of work is instrument cooling. Minimizing vibration is understood to be a key requirement for any AO-assisted telescope. Vibration has been (and continues to be) a limiting factor on the AO performances of instruments on existing telescopes, and a particularly bothersome source of vibration has been the instrument cryocoolers themselves. The cryogenic group at the Technical Institute for Physics and Chemistry (TIPC) is looking at gas turbine expanders to provide cooling to TMT instruments. These expanders use high RPM gas bearings that result in very low vibration, and this promising technology is being prototyped on scales needed for TMT.

4. Future science instruments

4.1 *Development program*

The development of new, powerful instruments is essential to fully exploit the scientific capabilities and maintain TMT at the forefront of international astronomical research. It is driven by the recognition that capabilities similar to the planned instrument suite shown in Table 2 are required to fulfill the TMT science mission, and that these capabilities will be needed as soon as possible after first light. It is important to emphasize that 'future instruments' here includes both Adaptive Optics (AO) systems and science instruments, and every science instrument beyond the three first-light instruments is considered to be a future science instrument.

There is strong interest from all TMT partners in participating in instrument projects. This is driven primarily by the interests of their respective science communities. The TMT partnership involves countries and institutions that are distributed over large geographical distances and are used to different development models. They bring a broad range of facilities and capabilities to the TMT instrumentation effort. The potential is exciting, and significant efforts are already under way to achieve the goal of building instrument partnerships that make sense scientifically and technically while satisfying partner aspirations.

Beyond the current work on the first-light instrument suites, a number of teams are looking over existing and new designs for the next generation of instruments. It is very important to emphasize that the future instrument concepts shown in Table 2 may or may not be the ones that will actually be built. These concepts were studied at the feasibility level back in 2005 and 2006, and new ideas are sure to emerge from regular reassessments of scientific priorities by the Science Advisory Committee based on regular community input. For example, a Japan–United States team is currently revisiting the concept for a mid-infrared Echelle spectrometer (MIRES) on

TMT. The new concept for the Mid-IR Camera, High-disperser, and IFU (MICHI) spectrograph (Packham *et al.* 2012) will include imaging and low spectral resolution modes.

Future instrument development will be the responsibility of the TMT Instrument Development Office (IDO). This is a joint AO and science instrumentation engineering team that will provide oversight for all instrumentation activities (except routine support). It will play a central role within the diverse TMT partnership. The IDO will initially be primarily occupied with the first-light instruments and associated AO systems (MOBIE, IRIS, IRMS, LGSF and NFIRAOS) with an increasing shift of effort towards support for future instruments and AO systems.

The IDO will have its own annual development fund of $12 million per year, and this fund will be kept separate from observatory operations. It will be used for building some of the more modest instruments in the planned suite and/or for funding the earlier development stages of the more ambitious, more complex ones.

The prioritization of future TMT instruments must be driven by scientific objectives. This is the cornerstone of the development program, and it will therefore be the responsibility of the TMT SAC. However, prioritization is not only a matter of science. All available information on technical readiness, schedule, and cost will also enter instrument decisions made by the SAC.

The development process is expected to include the following steps:

- SAC consults with the broader TMT user community, discusses instrument options and requirements based on desired science, technical readiness, schedule and cost, and prioritizes the next few instruments and makes recommendations to the TMT Board.
- TMT Board establishes guidelines (including scope and cost targets) for design studies.
- Two approximately one-year competitive conceptual designs are initiated for each desired instrument concept.
- SAC makes recommendations based on the outcome of studies (scientific capability, priorities, options, etc.).
- The Observatory (and Board) negotiates cost and scope of instrument contract awards taking partnership issues into consideration.
- TMT provides project management oversight for all instruments:
    - To ensure compatibility with overall Observatory system.
    - To maximize operational efficiency, reliability and minimize cost.
    - To encourage common components and strategies.
    - To ensure that budgets and schedules are respected.

Instrumentation phasing scenarios based on the 2006 feasibility studies for the TMT future instrument concepts were used to determine the appropriate level of funding for new instrumentation development during TMT operations. The phasing scenarios were devised based on input from the TMT SAC. The scenarios explore three basic variables: the list of desired instrumentation capabilities, their sequencing, and their arrival rate at the Observatory. These three variables dictate the funding impact of a given scenario in terms of the total funds required prior to first light and the annual funding required thereafter. Attention must also be paid to the arrival rate of instruments at the Observatory to ensure that realistic commissioning plans can be developed and implemented. The preferred SAC phasing scenario has one new instrument capability arriving every 2.5 years on average. This preferred scenario includes major AO upgrades such as an Adaptive Secondary Mirror (AM2) and a NFIRAOS upgrade in addition to the full list of science instruments in Table 2. According to the desired arrival rate, TMT would then have five instruments in operation within five years of first light.

4.2 *Community explorations*

The first step of the future instrument development process is especially important because community explorations are where new instrumentation ideas for TMT are born. They are meant to inform the prioritization of desired TMT instrumentation capabilities by the TMT SAC. Even though not all community explorations will be initiated by SAC, SAC will play a central role in coordinating them through the TMT Instrumentation Development Office (IDO). Community explorations will be used by SAC to draft initial science requirements (and their rationale) at a level of detail sufficient enough to avoid misunderstanding and potentially wasted efforts.

Given that both the scientific and technical landscape can change significantly over time, it is important to survey both on relatively short timescales (∼1 year). Explorations are therefore expected to provide a constant stream of information to SAC even though it calls for more advanced development phases and may be issued at less frequent intervals (∼2–3 years).

Community explorations will be open to unsolicited proposals and new technological development ideas. Explorations will also guide SAC in suggesting a cost cap for a given scientific capability to ensure that instrument teams are given clear cost guidance from the start.

TMT will hold workshops on science and instrumentation on a regular basis, and white papers will be solicited from the community. The focus of these consultations will vary. Some such as the TMT science and instrumentation workshops held in 2007 and 2011 covered as broad a range of science and technical topics as possible, but other consultations will focus on more specific science areas and technical concepts. It is important to note there will also be regular announcements that TMT is open to unsolicited instrumentation proposals.

TMT is planning to explore exciting options as they present themselves with relatively short, modest 'mini-studies' at the feasibility level. Mini-studies may include:

- Study of the science potential of a given instrument capability.
- Technology testbeds. e.g., new coronographs, wavefront sensors and control algorithms.
- Full feasibility studies.

SAC and IDO will work together on deciding which mini-studies to fund, and these discussions between the SAC and the IDO may occur more frequently than SAC meetings. A decision to support a mini-study will be dependent upon a solid connection with the current prioritized list of instrumentation capabilities (or alternatively an innovative new science case and instrumentation concept), a preliminary assessment of cost and technical feasibility, a good team track record and the leveraging of external support by matching funds.

5. Summary

TMT has a powerful suite of planned science instruments and AO systems that will make the Observatory a word-class, next-generation facility. The work on the first-light instruments including many prototypes is progressing very well. Many elements of the instrumentation development program such as prioritization by the TMT SAC and instrument scenarios are already being defined and discussed.

The development of TMT instruments represents a large, long-term program that offers a wide range of opportunities to all TMT partners.

Acknowledgements

The TMT instrument program is the collective work of numerous people at institutes around the world. Their enthusiasm and hard work drive TMT's progress towards designing and building cutting-edge, first-light and future instruments that will allow TMT to fully realize its exciting scientific potential.

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.

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