Earth Moon Planet (2009) 105:65–72
DOI 10.1007/s11038-009-9329-4

Solar System Capabilities of the Thirty Meter Telescope

David Crampton · Luc Simard

Received: 9 February 2009 / Accepted: 29 May 2009 / Published online: 17 June 2009

Abstract The TMT Project is completing the design of a telescope with a primary mirror diameter of 30 m, yielding ten times more light gathering power than the largest current telescopes. It is being designed from the outset as a system that will deliver diffraction-limited resolution (8, 15 and 70 milliarcsec at 1.2, 2.2 and 10 microns, respectively) and high Strehl ratios over a 30 arcsecond science field with good performance over a 2 arcmin field. Studies of a representative suite of instruments that span a very large discovery space in wavelength (0.3–30 microns), spatial resolution, spectral resolution and field-of-view demonstrate their feasibility and their tremendous scientific potential. Of particular interest for solar system research, one of these will be IRIS (Infrared Imaging Spectrometer), a NIR instrument consisting of a diffraction-limited imager and an integral-field spectrometer. IRIS will be able to investigate structures with dimensions of only a few tens of kilometers at the distance of Jupiter. Two other instruments, NIRES and MIRES (Near- and Mid IR Echelle Spectrographs) will enable high angular, high spectral resolution observations of solar system objects from the ground with sensitivities comparable to space-based missions. The TMT system is being designed for extremely efficient operation including the ability to rapidly switch to observations with different instruments to take advantage of "targets-of-opportunity" or changing conditions. Thus TMT will provide capabilities that will enable very significant solar system science and be highly synergistic with JWST, ALMA and other planned astronomy missions.

Keywords ELT telescopes · Ground-based instrumentation · Ground-based solar system research

D. Crampton (✉) · L. Simard
TMT Project Office, Pasadena, USA
e-mail: crampton@tmt.org; David.Crampton@nrc.ca

D. Crampton · L. Simard
Herzberg Institute of Astrophysics, Victoria V9E 2E7, Canada

1 Introduction

The TMT Project is planning construction of a 30 m telescope that is being designed from the outset as a system that will deliver diffraction-limited images at wavelengths longer than 1 micron. Many science programs will thus realize the D^4 advantage in point source sensitivity inherent in such a telescope. The TMT resolution at 1 micron will be 7 milli-arcsec, equivalent to $\sim$25 km at 5AU (Jupiter) or 0.035AU at 5pc (nearby stars), making TMT extremely powerful for studies of objects in our solar system and extra-solar planetary systems. The system is also being designed for rapid response, another important capability for solar system research, and it is being optimized to ensure that the operational efficiency is higher than realized on previous telescopes. The design and development phase of the TMT project is nearing completion. Since science operations are expected to begin a few years after JWST and ALMA come into full operation, opportunities for synergy have been prominent during discussions about priorities for TMT and its instruments.

The TMT Scientific Advisory Committee (SAC) has produced a Detailed Science Case that gives examples of the power that TMT will have to tackle a very broad range of scientific problems stretching from studies of first light objects to nearby solar system targets. Some examples of the latter are briefly discussed below. Undoubtedly, however, the legacy of TMT will be much greater: history amply demonstrates that many, if not most, major discoveries cannot be forecast a decade in advance, especially as new and novel instrumentation and technology are employed to enhance capabilities.

2 Instruments and AO Systems

The TMT SAC has identified a suite of adaptive optic (AO) systems and eight instruments to tackle the science that they envisage for the first decade of operation. Six of the instruments use built-in AO systems or use the Narrow Field Infrared Adaptive Optics System (NFIRAOS, the facility NIR Multi-Conjugate AO system) to exploit the diffraction-limited capability of TMT. As shown in Table 1, several AO systems, including a multiple laser guide star facility, are being integrated into the observatory system. The first three instruments listed in Table 2 are being constructed for operation at first light.

As shown in Fig. 1, the instruments and AO systems will be located in two large Nasmyth structures, addressed by an articulated tertiary mirror. This will enable rapid (less than 10 min) switching between on-sky observations of targets with different instruments, and less than 5 min with the same instrument.

3 Solar System Observations with TMT Instruments

Although all the instruments planned for TMT will undoubtedly be used for research of solar system targets, here we describe only three of them to illustrate the tremendous potential of TMT. The NIR facility AO system will deliver much better performance than AO systems on current telescopes mostly due to the fact that it will provide compensation for ground-layer effects and high altitude atmospheric effects simultaneously using artificial guide stars generated by six laser beacons. Careful analyses and optimization of the complete optical system (including all the mirror control and opto-mechanical systems of the telescope) are being carried out to ensure that NFIRAOS will deliver images from

Table 1 Summary of instrument capabilities and top-level requirements for adaptive optics

Instrumentation capability (and AO mode)	Field-of-view	Spectral passband, μm	AO performance requirements	Special requirements
Narrow field, near-IR spectroscopy and imaging (MCAO)	10–30 arcsec	1.0–2.5 (goal 0.6–2.5)	Delivered RMS wavefront error (WFE) of 180 nm at first light	2% differential photometry; differential astrometric accuracy of 1% of image FWHM
Narrow field, mid-IR spectroscopy and imaging (MIRAO)	10 arcsec	2.9–18 (goal 2.9–28)	Delivered RMS WFE < 500 nm (goal 300 nm)	Increase N band background by at most 15%
Wide field spectroscopy (GLAO-Ground Layer AO)	77 sq. arcmin	0.31–1.0 (goal 0.31–1.5)	"Enhanced seeing" to reduce integration times	
Multi-object, near-IR integral field unit spectroscopy (MOAO)	Multiple 2–5 arcsec objects within a 5 min region	0.6–2.5	50% enclosed energy within a 0.05 sec square pixel	
High contrast imaging and IFU spectroscopy (ExAO)	2 arcsec	1–2.5	Contrast ratios of 10^6–10^8 at separations of 0.05–1.0 s	IR WFS guide star magnitude $m_H < 10$

0.8–2.5 microns that have higher strehl ratios than currently realized, and over a wider field (30″ for full correction; up to 2′ with partial correction). It will also be able to utilize extremely faint guide stars and thus have very high sky coverage, even at the galactic poles. As an example of its potential for solar system research, in Fig 2 images of Io produced by the current Keck AO system are compared to simulated images from a very high strehl system if it were mounted on Keck, and from TMT NFIRAOS. The resolution delivered by TMT will rival that of many of the space missions on journeys to explore the solar system—with the advantage that TMT will also provide opportunities for the study of transient events and long term monitoring—and with higher spectral resolution.

The ability of TMT to rapidly switch instruments is key for projects that require monitoring or quick response for "targets-of-opportunity". Examples of the power of this for solar system objects can be gleaned from the sequence of Gemini and Keck AO images of Titan spread over 82 nights that demonstrate that the geography of the surface controls the mid-latitude clouds (e.g., see http://www.gemini.edu/node/115 and Roe et al. 2005), or the series of AO images of the rings of Uranus that demonstrate unexpected variability (e.g., see http://www.keckobservatory.org/article.php?id=139 or de Pater 2007b). As another example of the importance of temporal monitoring, Marchis et al. (2005) built a snapshot of Io volcanic activity (in only 1 h of Keck telescope time over 10 nights) with complete spatial coverage, something not possible with, e.g., the Galileo spacecraft. The 26 active and young volcanic centers that they observed have a total output of $\sim$0.5 Wm^{-2}, compatible with the expected heat production rate predicted by evolutionary model of Io, Europa and Ganymede into the Laplace resonance.

Table 2 The first decade instrument suite proposed by TMT SAC

Instrument	Field-of-view/slit length	Spectral resolution	λ (μm)	Comments
InfraRed imager and spectrometer (IRIS)	<3″ IFU >15″imaging	>3,500 5–100 (imaging)	0.8–2.5 0.6–5 (goal)	NFIRAOS
Wide-field optical spectrometer and imager (WFOS)	>40 arcmin^2, >100 arcmin^2 (goal); Slit length >500″	1,000–5,000 >7,500 @0.75″ (goal)	0.31–1.0 0.31–1.5 (goal)	Seeing-limited; GLAO
InfraRed multislit spectrometer (IRMS)	2 arcmin field 46 deployable slits	$R = 4{,}660$ @ 0.16 arcsec slit	0.95–2.45	NFIRAOS
Multi-IFU imaging spectrometer (IRMOS)	3″ IFUs over >5′ diameter field	2,000–10,000	0.8–2.5	MOAO
Mid-IR AO-fed echelle spectrometer (MIRES)	3″ slit length 10″ imaging	5,000–1,00,000	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	20,000–1,00,000	1–5	NFIRAOS
High-resolution optical spectrometer (HROS)	5″ slit length	50,000	0.31–1.1 0.31–1.3(goal)	Seeing-limited
"Wide"-field AO imager (WIRC)	30″ imaging field	5–100	0.8–5.0 0.6–5.0 (goal)	NFIRAOS

3.1 Infrared Imager and Integral Field Spectrograph (IRIS)

IRIS will be located on the bottom port of NFIRAOS, and will be able to conduct diffraction-limited imaging and integral-field spectroscopic observations in the 0.8–2.5 micron wavelength region. The imager will have a field-of-view of 15 arcsec and will have 4 milliarcsec pixels to adequately sample the J band images. IRIS will provide several different plate scales for integral field spectroscopy ranging from 4 to 50 milliarcsec and fields-of-view up to 3″. It is planned to use a lenslet system for the finest plate scales—such systems best preserve the wavefront quality delivered by the AO system since the spatial resolution is defined at the entrance. An image slicer system will be used for coarser scales since these systems provide more optimal use of the detector area and offer gains in sensitivity. Astrometric measurements with precisions of a few tens of microarcsec are foreseen with the IRIS imager.

As Fig. 2 indicates, the spatial resolution of TMT will make it possible to obtain detailed images and spatially resolved spectra of satellites such as Io, Europa and Titan, and to monitor activity of atmospheric and surface features such as clouds and volcanoes. The spectral resolution will be sufficient to derive precise measurements of temperatures and chemical compositions. An indication of what will be possible with TMT/IRIS is illustrated by the integral field observations with OSIRIS on the Keck AO system of a volcano (Tvashtar) on Io (Laver et al. 2007), the monitoring of atmospheric activity on

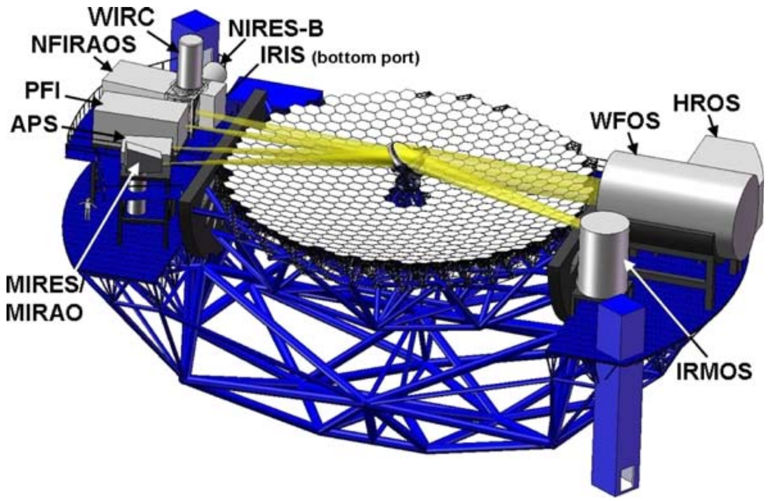

Fig. 1 The telescope will be a wide field Ritchey–Chretien telescope with a highly segmented 30 m primary mirror. The tertiary mirror located at the center of the primary will direct the beam to any of the instruments. The names of the instruments are given in Table 2. APS is the system used to align and phase the 492 segments of the primary mirror and the optical system as a whole

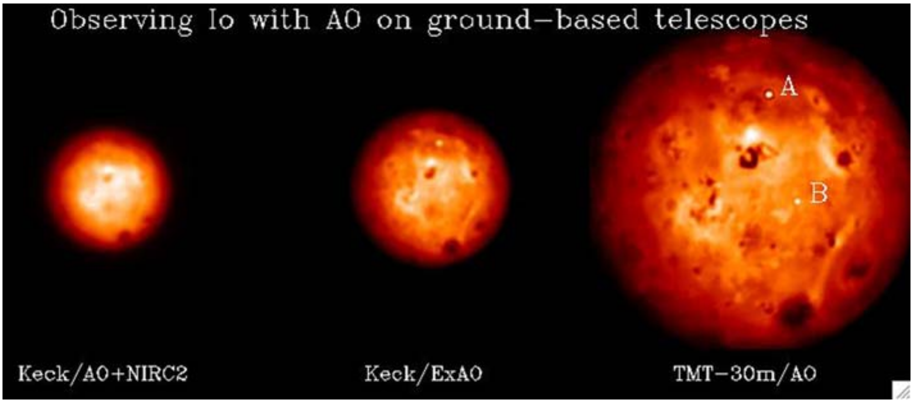

Fig. 2 Simulations of the spatial resolution achievable with TMT/IRIS compared to a very high strehl adaptive optics system on Keck (*middle image*) and with the current Keck AO system (*left*). (Marchis et al. 2007)

Titan by Ádámkovics et al. (2007), and the monitoring of Io by de Pater et al. (2007a). TMT MCAO images will have $\sim 5\times$ better resolution than these ($3\times$ because of the larger aperture, more because of MCAO—see Fig. 2).

It will also be possible to determine physical characteristics of asteroids, trans-neptunian objects (TNOs) and Kuiper Belt Objects (KBOs)—several of them will be easily resolved by TMT. The study of the orbital elements of binary and multiple systems of TNOs down to very small sizes and out to large heliocentric distances will be possible yielding, among other things, precise measurements of their densities. These objects, which were detected relatively recently, arguably represent some of the best examples of pristine material in our solar system. Large numbers are now being discovered through surveys with CFHT, Pan-STARRS and other wide field imagers. TMT IRIS will have $\sim$200 km resolution at 40AU, enabling detailed studies of the largest bodies. A discussion of the potential of TMT and other planned facilities for studies of Kuiper Belt Objects has recently been published (Trujillo 2008), as well as a perspective on the exciting science that can be anticipated from them in the near future (Jewitt 2008).

3.2 Near IR Echelle Spectrometer (NIRES)

NFIRAOS will also be used to feed diffraction-limited images to a high spectral resolution (R $\sim$50,000) echelle spectrograph (NIRES-B) that will simultaneously deliver spectra over the whole accessible wavelength range 1–2.5 microns. Most important ices have strong features in the NIR and so this instrument and its redder clone [NIRES-R, operating in the 2.5–5 micron region behind a mid-IR AO (MIRAO) system] will be popular instruments for studies of the chemistry of solar system objects and of features on these objects. As an example, a spatially resolved map of the distribution of SO_2 ice on Io was recently obtained with the Keck AO system by Laver and de Pater (2008). High spectral resolution is key to understanding the complex spectra of solar system objects and for obtaining physical, thermal and dynamical information from the spectra. Applications include the mapping and monitoring of water, CO_2 and other molecules like methane (e.g., Mumma et al. 2009) in the atmospheres of major planets like Mars as well as dwarf planets like Pluto (e.g., Sicardy et al. 2003; Lellouch et al. 2009). TMT NIRES and MIRES will have $\sim$50$\times$ higher spectral resolution than the instruments on the space probe Cassini, for example. Being diffraction limited, the NIRES spectrographs need not be significantly larger than similar instruments now being built for 8–10 m telescopes, but it will be far more powerful (D^4 advantage for point sources).

3.3 Mid-IR Echelle Spectrometer (MIRES)

MIRES is a high spatial and high spectral resolution imaging spectrograph for the thermal (5–25 micron) infrared (Elias et al. 2006). MIRES will be fed diffraction-limited images by a MIRAO system using either its own deformable mirrors or an adaptive secondary if, or when, the latter becomes available. With its high spectral resolution and high sensitivity, MIRES enables science that is not possible with smaller telescopes or from space. For example, MIRES will have similar spectral resolution to TEXES (Lacy et al. 2002) but with a two orders of magnitude gain in sensitivity. In fact, due to the low background per pixel it is competitive in sensitivity to space based instruments, for example MIRI on JWST. Fig. 3 shows how it compares in angular resolution and sensitivity to other facilities. As is the case for NIRES, high spectral resolution is essential to disentangle and understand molecular features in infrared spectra and to derive physical, thermal and dynamical information from line profiles. The importance of high spectral resolution is nicely demonstrated by the discovery of propane on Titan by Roe et al. (2003). The sensitivities of MIRES and NIRES also provide the ability to measure very weak spectral features in high signal-to-noise spectra, allowing detection of rare molecular species. This has implications for our understanding of the origin of life on earth through the detection of the precursors of complex organic molecules, improving our understanding of the formation of pre-biotic molecules.

In imaging mode, MIRES will not have the raw sensitivity of JWST MIRI but it will have five times the spatial resolution, enabling it to investigate nearby debris disks at $\sim$1AU resolution.

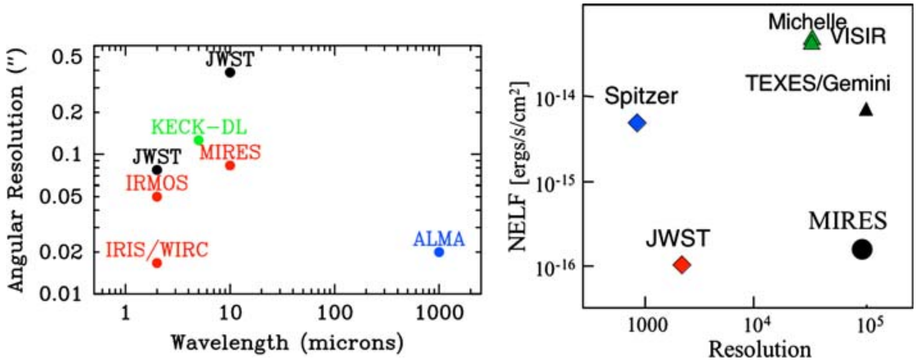

Fig. 3 (*Left*) The angular resolutions of TMT instruments nicely complement that of JWST and ALMA. (*Right*) For point sources TMT/MIRES will have comparable spectral line sensitivity (Noise Equivalent Line Flux computed at 10 microns) to infrared space missions but at a much higher spectral resolution

4 Exoplanet Observations with TMT

What key physical processes govern the formation of planets? What are the timescales and mechanisms for planet formation? How might life arise in such systems? TMT will have several instruments that will yield answers to questions like these with observations of exoplanets and debris disks. These will include:

- Doppler detection of planetary systems with HROS and NIRES
- Direct detection and characterization of planets around nearby stars with PFI
- Studies of the structure, composition and chemistry of debris disks with PFI and MIRES, especially in the inner regions (1–10AU) where terrestrial and giant planets form
- Studies of the atmospheres of extra-solar planets with IRIS, NIRES and MIRES

This is a relatively new, fertile field of astronomy that is increasingly active as new facilities are commissioned. TMT is well placed to make significant contributions.

5 Summary of TMT Solar System Capabilities

Heretofore space-based observations have been key to many of the advances in solar system research. TMT will herald a new era. Some of its relevant capabilities will be:

- Spatial resolution equivalent to that of many fly-by space probes, especially in the outer solar system
- Spectroscopy over a wide wavelength range (0.3–30 micron) with very much higher spectral resolution than space probes
- Sensitivity equivalent to JWST and ALMA
- Temporal monitoring capabilities
- Quick response for transient or unpredictable events (e.g., impacts, eruptions)
- Precision (tens of microarcsec) astrometric capability
- Precision (meters per second or better) line-of-sight velocity capability

The above is intended to illustrate the potential of TMT for solar system observations. Many more examples and details of programs enabled by TMT and its instruments are discussed in the series of “foundation documents” available at tmt.org.

Acknowledgements We thank Chad Trujillo, Franck Marchis, JJ Kavelaars and Al Conrad for generously providing information and images of solar system targets that materially contributed to our understanding of current solar system research. We also thank the anonymous referee for his/her suggestions. The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. 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.

References

M. Ádámkovics, M.H. Wong, C. Laver, I. de Pater, Science **318**, 962 (2007)
J.H. Elias et al., Proceedings of the SPIE **6269**, 122 (2006)
D. Jewitt, astro-ph 0811.2265 (2008)
J.H. Lacy, M.J. Richter, T.K. Greathouse, D.T. Jaffe, Q. Zhu, Publ. Astron. Soc. Pac. **114**, 153 (2002)
C. Laver, I. de Pater, Icarus **195**, 752 (2008)
C. Laver, I. de Pater, F. Marchis, Icarus **191**, 749 (2007)
F. Marchis et al., Icarus **176**, 96 (2005)
F. Marchis, J.R. Spencer, R.M.C. Lopes, in *Io After Galileo*, ed. by R.M.C. Lopes, J.R. Spencer (Praxis, Chichester, UK, 2007)
E. Lellouch et al., Astron. Astrophys. **495**, 17L (2009)
M.J. Mumma et al., Science **323**, 1041 (2009)
I. de Pater, H.B. Hammel, M.R. Showalter, M.A. van Dam, Science **317**, 1888 (2007a)
I. de Pater, C. Laver, F. Marchis, H.G. Roe, B.A. Macintosh, Icarus **191**, 172 (2007b)
H.G. Roe, T.K. Greathouse, M.J. Richter, J.H. Lacy, Astrophys. J **1086**, 3798 (2003)
H.G. Roe, M.E. Brown, E.L. Schaller, A.H. Bouchez, C.A. Trujillo, Science **310**, 477 (2005)
B. Sicardy et al., Nature **424**, 168 (2003)
C.A. Trujillo, in *The Solar System Beyond Neptune*, ed. by M.A. Baruchi, H. Boehnhardt, D.P. Cruickshank, A. Morbidelli, University of Arizona Space Science Series (University of Arizona Press, Tucson, 2008), p. 573