Key Science Drivers for MICHI: A MIR Instrument Concept for the TMT

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ABSTRACT

We discuss the key science drivers for a mid-IR instrument for the 30 m TMT, taking advantage of the spatial and spectral resolution afforded by the large aperture of the TMT.

1. INTRODUCTION

The *Thirty Meter Telescope* (TMT) is a next-generation ground-based telescope with a 30 m aperture constructed from 492 mirror segments. The chosen site is Mauna Kea, offering exceptional infrared (IR) qualities and enabling synergy with the many observatories operational at that location. The TMT will enable a revolution in light-gathering power and very sensitive diffraction-limited spatial resolutions with suitable adaptive optics (AO) systems. In the mid-infrared (MIR, 7.5–26 μm) region, the TMT will afford ~15 times higher sensitivity than ground-based 8 m class telescopes and a spatial resolution of ~55 milli-arcseconds (mas) at 8 m with a MIR AO system. Both *SPICA* and the *James Webb Space Telescope* (*JWST*) will feature outstanding sensitivity, but at a spatial resolution >4.6 times inferior to the TMT. Where broadband sensitivity is critical, *SPICA* and/or *JWST* will be clearly the instruments of choice, but where spatial resolution is key, a MIR instrument on the TMT will be crucial. In the *Spitzer* and 8 m era, we have already witnessed the synergy of those observatories at MIR wavelengths, where *Spitzer*'s sensitivity is used in tandem with 8 m spatial resolution.

Additional to high spatial resolution, the TMT's huge light gathering capacity opens a new window of very high-dispersion (R~10^5) spectroscopy, which has thus far rarely been used at MIR wavelengths. The 10 μm optimized high spectral resolution instrument TEXES (R~10^5) has been used for three science campaigns on Gemini, producing results as varied as a spatially resolved study of Neptune stratospheric heating and cooling (Greathouse et al. 2011), demonstrating a new technique for establishing the effective temperature in low mass dwarf stars (Viti et al. 2008), and spectrally resolved C_2H_2 absorption toward the nucleus of a ULIRG (Lahuis et al. 2007). The bulk of the TEXES/Gemini work deals with star formation regions: disc gas emission (e.g. Najita et al. 2009), molecular absorption from gas along the line of sight (Knez et al. 2009), and tracing dynamics of ionized gas near embedded, massive star forming regions (Lacy et al. 2007). TEXES was offered on Gemini in 2013B, and was oversubscribed by ~3. These papers tantalizingly demonstrate the promise of such high spectral resolution combined with high spatial resolution, which will be greatly enhanced on a 30 m-class telescope.

Recently, we, a collaborating group of MIR astronomers based predominantly in the USA and Japan have further studied MIR science drivers in varied astronomical fields. We find that a MIR capability on the TMT is essential to make progress in several fields, and especially those of disc and planet formation/evolution, solar system objects, lifecycle of materials in the universe, extragalactic super massive black holes, star formation and activity in galaxies, and cosmology (Okamoto et al. 2010). Based on these studies, we modified the design of MIRES (Elias et al. 2006), a planned MIR instrument for the first decade of TMT operation to address these science cases. We call this instrument MICHI, the **MI**R **C**amera, **H**igh-dispersion spectrometer, and **I**FU, where a feasibility level design is described by Tokunaga et al. (2010).

2. MICHI SCIENCE CASES

We investigated the (a) transformative and (b) broad science cases enabled through MIR on the TMT. Science requirements were flowed to instrument requirements, later addressed by our feasibility-level design. Below we highlight MICHI transformative science 'threads' in the areas of disc and planetary formation/evolution, exoplanet, and extragalactic astronomy. Additional cases of lifecycle of materials and formation/evolution of dust grains are omitted for space reasons. The science is leveraged from the huge increases in spatial resolution and light gathering capacity pushing ground-based MIR astronomy past a tipping point in target numbers, leading to order(s) of magnitude increase in available targets.

2.1. High Spectral Resolution Science Drivers

TMT will advance MIR high-resolution spectroscopic studies from the current level, where most studies concentrate on the brightest 5–10 objects of a given class, to where a comparative study of ~100 objects with good signal-to-noise ratio (SNR) is entirely practical. This arises from the raw sensitivity gain that scales as D^2 and the improvement in the time to reach a given SNR for an object that scales as D^4. For example, a typical solar mass T Tauri star can be studied in a volume that extends past Orion as opposed to only reaching Taurus with 8 m telescopes — this permits study of cluster star formation, not just formation in small aggregates. With the TMT, objects ~3 magnitudes fainter become accessible; 8 m surveys requiring **10 hours** of integration time per target will require **3 minutes** to reach the same SNR.

The larger aperture, when coupled with a high-Strehl AO system, translates into a radically improved spatial resolution and smaller enclosed energy radius. With the TMT, the 10 μm spatial resolution of 70 mas corresponds to ~10 AU at 140 pc, the distance of nearby star forming regions. With the high SNR enabled by TMT, spectroastrometry becomes feasible for atomic, ionic, and molecular features from disk gas. Spectroastrometry of 4.7 μm CO lines with the VLT has provided sub-mas precision (Pontoppidan et al. 2011). Scaling by the aperture of TMT, this suggests spectroastrometry could provide information down to ~0.03 AU in nearby star forming regions close to the star where dust evaporates. MIR high spectral resolution has many significant benefits, including:

- Providing access to the line profile which enables the study of dynamics.
- Maximal sensitivity to intrinsically narrow features, such as those in quiescent gas.
- Separation of neighboring features enables study of weak features close to strong ones, and enables study of scientifically interesting features lying close to obscuring lines from Earth's atmosphere; with high-resolution and a good site, such as Mauna Kea, Earth's orbital velocity often Doppler shifts telluric lines off of the desired target lines.

2.2. Discs and Exoplanet Science Drivers

Exoplanets observations have rapidly advanced, revealing surprisingly diverse exoplanetary systems. Observations of planet forming regions, protoplanetary and debris discs, have revealed astonishing pictures of planet forming discs such as spirals, gaps, holes, and dips, strongly implying that planets are forming there. Dust evolution, the key ingredient of planets, through grain growth and crystallization, has been observed. An ideal wavelength to characterize dust and planets is the MIR, because it has many key spectral features. However, such studies are limited from 8 m class observatories by the combination of limited (a) spatial resolution and (b) sensitivity. Both limitations will be greatly reduced by observations from the TMT. Thus studies of discs and exoplanets are promising science drivers for TMT/MICHI.

2.3. Extragalactic Science Drivers

A full understanding of the relationship between the SMBH and host galaxy, as well as any activity, will help to address two crucial questions in cosmology: (1) which formed first, the SMBH or the galaxy, and (2) how did SMBHs form so shortly after the big bang?

THE AGN TORUS

AGN are largely explained in the context of a unified theory, by which a geometrically and optically thick torus of gas and dust can obscure the AGN central engine from some lines of sight. The exact properties of the torus remain uncertain, and there are still several open questions: (a) What is the nature of the torus material and its connection with the ISM of the host galaxy, (b) How do the properties, such as, geometry and optical depth, of the torus depend on the AGN luminosity and/or activity class, (c) Do the dust properties change with the AGN luminosity/type, (d) What is the role of nuclear ($\leq$100 pc) starbursts in feeding and/or obscuring AGNs, and (e) How is the fueling of AGN achieved? Observations at MIR wavelengths are essential to these investigations as the torus intercepts and re-radiates a substantial amount of flux from the central engine, peaking in the MIR, and the level of contamination from stellar emission is greatly reduced compared to optical/near-IR observations.

The torus is compact (few pc) in moderate activity AGN (i.e. Packham et al. 2005; Mason et al. 2006), and perhaps absent in low activity AGN. The torus structure was revealed to be best described by a 'clumpy' distribution of gas (Nenkova et al. 2002), rather than a homogeneous distribution of dust. Tentative new results seem to show the precise torus structure and perhaps presence is strongly affected by the level of activity in the AGN, which in turn is related to the fueling of the central engine. A systematic survey of AGN tori is in progress using 8 m class telescopes (Alonso-Herrero & Packham 2013), but this is confined to the local universe due to the combination of (a) flux and (b) spatial resolution limitations. Through the ~3.75 times increase in the diffraction limit (and at a much higher Strehl ratio when using a MIR AO system on the TMT, as compared to the tip/tilt correction often used on existing 8 m class observatories), observations of fainter and/or more distant objects can be performed. At z=0.5, the spatial resolution of *JWST*/MIRI is 1.5 kpc and is hence heavily contaminated by galactic star forming rings, etc., whereas the TMT spatial resolution is 330 pc and is nuclear dominated. Through careful imaging and spectral observations of the torus in $z\leq$0.5 objects, templates can be produced that will be of crucial importance to calibrating and interpreting observations from *JWST* and *SPICA*. Only through combined results will an accurate examination of the torus properties, effect of radio loudness, and the host galaxy versus both the level of AGN activity and redshift be probed. Further, the *WISE* all-sky survey will use colors of the sources to search for and characterize type 2 QSOs, for which MICHI will be ideal to perform the detailed follow-up examinations, with the aim of modeling and parameterizing the torus of these objects, allowing a thorough comparison to other AGN classes.

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