TMT/MICHI current concept

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ABSTRACT

A thermal imager and spectrometer is being investigated for possible construction in the early operation of the Thirty Meter Telescope (TMT). Combined with the mid-IR adaptive optics (AO) system (MIRAO), the instrument will afford 15 times higher sensitivity and 4 times better spatial resolution (0.″07) with a greatly improved and stable Strehl ratio at 10 μm compared to the images delivered by the fast guiding systems of 8m-class telescopes. Through exploiting the large collecting area of the TMT, a high-dispersion spectroscopy mode unrivaled by other ground- and space-based facilities is planned. Such capabilities offer the possibility for breakthrough science, as well as workhorse observing modes of imaging and low/moderate spectral resolution.

Keywords: mid-IR, TMT, instrument

1. MICHI: A THERMAL IR INSTRUMENT CONCEPT FOR TMT

Ground-based facilities and space-based facilities have been complemental with each other. For example, current 8m-class telescopes contributed many follow-up studies of sources discovered by space-based satellites such as *AKARI*. In the next coming decades, new space-based facilities such as *JWST* will also provide many interesting sources, thus next generation ground-based facilities such as TMT, EELT, GMT, and so on will also become important.

We have been proposing a thermal IR instrument for TMT. Originally in 2006, a Mid-IR Echelle Spectrometer (MIRES) with mid-IR Adaptive Optics (MIRAO) was proposed for the TMT First generation instrument (Elias et al. 2006; Chun et al. 2006). Although it established the TIR as an important scientific goal for the TMT, it was not accepted as the first generation instruments for the TMT unfortunately. After that, Japan and other partners joined the TMT project, and the ground-based mid-IR researchers in US and Japan started to discuss the possible mid-IR instrument concept for TMT. Adding mid-IR imaging, low-resolution spectroscopy, and IFU capability to MIRES, we proposed a new mid-IR instrument concept MICHI for TMT (Tokunaga et al. 2010; Okamoto et al. 2010; Packham et al. 2012). The first MICHI concept was mostly focused on N- and Q-bands (so-called 10 and 20 μm atmospheric windows), however, increasing scientific demands for L- and M-bands (3–5 μm) and technological changes such as new detectors, we decided to include shorter thermal infrared wavelengths (L- and M-bands) to MICHI capabilities. Since the latest MICHI concept is more optimized for shorter thermal IR wavelengths, we sometimes call it a 'blue MICHI' concept.

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2. TMT/MICHI SCIENCE CASES

Thanks to the large aperture provided by TMT, the instrument will afford 15 times higher sensitivity and 4 times better spatial resolution compared to the instruments on 8m-class telescopes. A high-dispersion spectroscopy mode also provide important capabilities to probe the unique parameter space. Such capabilities offer the possibility for breakthrough science, as well as workhorse observing capabilities. For the breakthrough sciences, we will briefly introduce some science cases towards exoplanets, protoplanetary disks, and active galactic nuclei (AGN).

2.1. exoplanets: direct detection and characterization

The era of the TMT will see the continuation of the change of emphasis from discovery to detailed characterization of exoplanets. The 8m's are approaching their limits due to both flux and spatial resolution, and whilst the *JWST* will make major progress due to its outstanding sensitivity, its spatial resolution will leave large discovery spaces open. In particular, the detection and characterization of Earth-like exoplanets is the next major breakthrough in the field of exoplanets. *Kepler* revealed the ubiquitous nature of the rocky planets around Sun-like star. While some Earth-size rocky exoplanets have been found using the transit and radial velocity techniques, no Earth-like exoplanets have yet been discovered so far. It requires direct detection and characterization of the candidate exoplanets. Direct imaging and characterization of candidate habitable planets are planned mostly in the visible-band using reflected light from such planets by dedicated future space missions. TMT/MICHI's 10 μm coverage is highly complementary to these missions. Especially, contrast ratio (CR) between central star and the exoplanets could be lowered from 10^{-10} (visible) to 10^{-7} (mid-IR), thus TMT with MICHI could be the first instrument capable of finally finding a real 2nd Earth. Key targets for the Northern hemisphere include Tau Ceti (with known Earth-size radial velocity exoplanets, with 2 planets within the habitable zone), Epsilon Eridani, and 61 Cygni A/B. TMT/MICHI will be capable of imaging and spectroscopy of the 2nd Earths (habitable planets) around nearby Sun-like stars up to 5 pc at 10 μm.

Furthermore, the combination of high spatial/spectral resolution and sensitivity leaves this clearly the domain of the 30m class of telescopes. A TIR high-dispersion spectrometer (HDS) permits high-resolution spectroscopy of (super-)Earths to hot Jupiters and provides unique insights into the atmospheric dynamics, composition, and chemistry of these objects; and in a few cases, into their spin and orbital angular momenta, and possibly global weather patterns. MICHI could therefore easily become TMT's workhorse for measuring atmospheric metallicity through O and C measurements, and for measuring the ratio of these two elements (C/O). The L- and M-band provides access to all major O- and C-bearing molecules, such as H_2O, CH_4, CO, CO_2, thus constraining exoplanet atmosphere model and its formation origin in the protoplanetary disk. In addition, even rotation rate and/or wind/circulation structure of exoplanets can be measured by cross-correlating with the template atmospheric spectra (Snellen et al. 2014) and/or Doppler imaging technique (Crossfield 2014).

2.2. protoplanetary disks

As the parent object of exoplanets, the investigations of protoplanetary discs will remain a subject of intense scrutiny. Giant planets grow directly from the primordial disc, while the constituents of terrestrial planets form and eventually coalesce over the next 10's of Myr. Whether planets have chemical compositions that foster the creation and development of life depends on the chemical abundances of the planetesimals that eventually form these planets, thus understanding chemical, physical structure of the disk is important. Of particular note, the snow lines of water and other volatile molecules (Blevins et al. 2016) play an important role in planetary formation, metal mass fraction in formed planets (Öberg et al. 2011), and eventually the chances for habitability. The snow lines of volatiles may also be critical in causing changes in dust structures that help to foster grain growth and the triggering of planet formation, which could explain the spectacular rings of HL Tau (Zhang et al. 2015) and other protoplanetary disc. TMT/MICHI will spatially/spectrally resolve snow lines of these species by observing emission lines and ice absorption features (e.g., Honda et al. 2016).

In the coming decades, the *JWST* will produce low-resolution TIR spectra of 100's of discs to understand the disc chemistry. However, emission line profiles that provide diagnostics of temperature and abundance vs spatial location will be lost due to lower spectral resolution. Such information will be recovered by high spectral resolution spectroscopy and the exquisite spatial resolution afforded by TMT/MICHI. This information is crucial as every improvement in spatial/spectral resolution has revealed unexpected structures in discs. Disc thermal structure changes can also be traced through the spatial distribution of crystalline silicate material in the disc. TMT/MICHI spatially-resolved TIR spectra will afford a unique opportunity to uncover both mineralogical evolution of solids and the transport of material within a disc (e.g., Okamoto et al. 2004).

Growing protoplanets will be detectable in two ways with IFU spectral images. First, spiral waves created by accreting planets should be detectable in CO and other molecules (Regály et al. 2014). Second, a growing giant planet may have a circumplanetary/proto-lunar disc, with a chemical and physical structure analogous to the much larger parent circumstellar disc. Evidence for a planet has already been seen in CO spectroastrometry in a ~10 AU planet around HD 100546 (Brittain et al. 2014); TMT/MICHI will push these detections to within an AU, where planets are much more prevalent.

2.3. Unravelling AGN & BH Astrophysics

It is observationally well known that supermassive black holes (SMBHs, $\geqq 10^6 M_\odot$) are ubiquitous in galaxy centers, and that the masses of SMBHs and galaxy stellar components are correlated. This strongly suggests that SMBHs and stars have co-evolved and that SMBHs play an important role in galaxy formation. Understanding this interplay remains a key scientific theme in modern astronomy. AGN are the primary objects in these studies as they are accreting surrounding gas and dust onto the SMBHs and exchanging gravitational energy to heat and thermal radiation. Observations of nearby AGNs have given rise to the generally accepted unified theory of AGNs. The theory postulates that a central accreting SMBH is surrounded by a geometrically and optically thick torus shaped dusty structure. Although the torus can naturally explain various observational results of AGNs, little is constrained about its physical/morphological properties due to its compactness (<10 pc or <0.″1 at $z > 0.005$), nor crucially its interaction to the host galaxy, creation nor maintenance; this is despite the torus being the cornerstone of the theory. Torus dust is heated by the AGN's radiation, peaking in the TIR regime. High spatial resolution observations at TIR wavelengths are the most powerful way to unravel the properties of the enigmatic AGN torus, and reduce contaminating radiation of the host galaxy. TMT/MICHI will play a crucial role in furthering this field by exploiting the combination high spatial resolution and high sensitivity imaging and low spectral resolution spectroscopy. We highlight some areas of particular exciting advances below.

First, dust emission from the torus will be spatially resolved for the first time using TMT/MICHI. Imaging and spectroscopy will provide invaluable information about the sizes, inclination angle, and dust mass in the torus. Model degeneracies which pertain in the conventional spectral energy distribution (SED) fitting methods will be resolved and we will be able to finally understand the nature of the dusty torus. Resolving degeneracies will allow distinguishing between the plethora of torus models which will finally permit a true characterization of the genesis and maintenance of the torus. In turn, this will clearly connect the torus to the host galaxy and elucidate their long-sought after connections. Some have suggested that the torus genesis and inflation is due to a magneto-hydrodynamic wind. If so, AGN polarimetry could significantly aid in estimating the magnetic field direction and properties. However, although much NIR AGN polarimetry data exists, only a handful have TIR polarimetric data, primarily due to the photon hungry nature of polarimetry and requirement for high spatial resolution. TMT/MICHI will greatly alleviate both limitations and thus permit such observations. Indeed, TMT's sensitivity gain will be so great that polarized nuclear inflow/outflow will be easily observable, linking the AGN to the galaxy dominated regions.

Second, observationally it is clear that the torus is geometrically thick but simple torus models gravitationally collapse it to a disc. Possible 'inflating' mechanisms are modeled to be AGN radiation pressure or supernovae explosions associated with nuclear star formation inside the torus and/or the surrounding ∼100 pc circumnuclear disk. As PAHs are excited in star-forming regions but are destroyed in the close vicinity of an AGN, observations of PAH emission features at 3.3 and 11.3 μm are ideal to distinguish between these models. IFU observations with TMT/MICHI in the relatively little extinction wavebands of L- or N-band are ideal to address this dichotomy.

Finally, for highly obscured AGN the physical conditions of material in front of the AGN can be determined from the absorption features of multiple P- and R-branches of CO 4.7 μm ro-vibrational emission lines. Moderate-resolution ($R \sim 5,000$) M-band spectroscopy uniquely combines high sensitivity and high spatial resolution to minimize contamination from extended star-formation activity and allow the pinpointing of the sightline toward the obscured AGN.

3. REQUIRED CAPABILITIES AND CURRENT MICHI CONCEPT

In 2008 we evolved the MIRES design to MICHI through (1) enhancing imaging capabilities, (2) adding low-spectral resolution, (3) adding an IFU, all of which operate at 7.5–26 μm. We also made early investigations of polarimetry and coronagraphy, but have not made a firm choice about their incorporation at this time. The work was leveraged from a preliminary optical design that achieved almost all of the requirements at that time. We then added feasibility-level discussions of all other instrument aspects, documented in a 136p reference document (Okamoto, Packham, & Tokunaga, 2010, available upon request). From this report, we presented the MICHI design and science cases in SPIE meetings by Okamoto et al. (2010), Tokunaga et al. (2010), and Packham et al. (2012). However, due to a combination of evolving science drivers and technical opportunities, combined with new collaborations, we have further evolved MICHI to be optimized for 3–14 μm, but are planning to make no technical decision that excludes the Q band. This scientific choice was dominantly made as (1) the 3–5 μm science cases are more numerous and stronger than those in the Q band, (2) the exoplanet community was excited for >2 μm on the TMT, (3) high-spectral resolution is especially strong at 3–14 μm; technical drivers include (4) the advent of significantly improved N band detectors, which operate at 3-14 μm, (5) the MIRAO 2006 design provides good correction to 3 μm, and could use technical advances to provide high Strehl (∼80%) correction to 3 μm, and (6) using immersion gratings from 3–14 μm affords a continuous high-spectral resolution capability to the TMT community.

The instrument is essentially an all-reflective design (except for the entrance window and possible polarimetric/coronographic optics), modular for optimized alignment and/or phased deployment, and compact to fit in the MIRES space envelope. It dominantly employs off-the-shelf components, with other components in advanced development/characterization phases. The design leverages experience from other similar TIR instruments (i.e. T-ReCS, COMICS, CanariCam, MIMIZUKU, TEXES, EXES, WINERED, MIRSIS, etc.) of team members had leading or significant role in their development. Thus we believe the instrument to be of relatively low cost and low risk.

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