The Key Science Drivers for MICHI: a thermal-infrared instrument for the TMT

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ABSTRACT

With the imminent launch of the JWST, the field of thermal-infrared (TIR) astronomy will enjoy a revolution. It is easy to imagine that all areas of infrared (IR) astronomy will be greatly advanced, but perhaps impossible to conceive of the new vistas that will be opened. To allow both follow-up JWST observations and a continuance of work started on the ground-based 8m's, we continue to plan the science cases and instrument design for a TIR imager and spectrometer for early operation on the TMT. We present the current status of our science cases and the instrumentation plans, harnessing expertise across the TMT partnership. This instrument will be proposed by the MICHI team as a second-generation instrument in any upcoming calls for proposals.

Keywords: Infrared, mid-infrared, thermal infrared, imaging, spectroscopy, high spectral resolution, adaptive optics, polarimetry.

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1. INTRODUCTION

We present in this paper highlights of the science cases for a possible thermal-IR instrument for the TMT that we call MICHI (**M**id-**I**R **C**amera, **H**igh-disperser & **I**FU spectrograph, 未知). In §2-5 we describe summaries of the TIR (3-14μm) driving science cases (exoplanets, protoplanetary disks, AGN/SMBH, and a representative selection of other cases respectively), §6 details the instrument feasibility, and §7 has concluding remarks. We are convinced our transformative and broad science cases show strong alignment to the TMT's Detailed Science Case (Skidmore et al. 2015), combined with low technical risk and inclusion of science/technical teams across the TMT make MICHI a compelling second-generation instrument.

2. EXOPLANETS

TMT/MICHI will be a transformative and unique exoplanet science instrument, through exploiting what some have called the "TIR advantage"[1,2]. The current generation of 10 m class telescopes (e.g. Keck, Subaru, Gemini, VLT) provided the first direct images and spectral characterizations of young Jovian exoplanets at 1-5 μm. Continuous development of instruments on these telescopes is maturing key exoplanet imaging methods and technologies, which MICHI will benefit from at longer wavelengths. While extremely sensitive at TIR, JWST's limited angular resolution prevents it from directly imaging and characterizing exoplanets at solar system-like scales (~1-25 AU) for all but the very nearest stars. With MICHI, TMT will leverage advances made by observatory partners that (1) open up both new exoplanet discovery space and new phase space for characterization and (2) complement exoplanet science with the possible PSI (Planetary System Imager).

2.1 TIR Imaging & Characterization of Solar Neighborhood Jovians to Earth-Size Exoplanets

TMT/MICHI provides a dramatic increase in angular resolution and orders of magnitude better sensitivity in the TIR (especially at 10 μm) compared to current ground-based telescopes. Current exoplanet imaging systems can probe young (1-100 Myr) Jovian planets, and possibly, in the near future with next generation or upgraded instruments, a few Jovians in reflected light. In both cases, however, direct detection of the many Jovian exoplanets indirectly identified by radial-velocity (RV) methods ($r > 1$ AU, orbiting older stars) and exo-Earths around Sun-like stars remain out of reach. TMT/PSI expects to image rocky exoplanets in reflected visible/near-IR (NIR) light around the nearest low-mass stars. In comparison, MICHI will be sensitive to cooler, Gyr-old Jovians orbiting nearby ($d < 10$ pc) stars, dramatically increasing the number of systems where planets can be detected, providing a substantial overlap with the RV found planet population. TIR characterization using both low- and high-resolution spectroscopy of Jovian exoplanets (including free-floating objects or similar mass) will probe non-equilibrium chemistry, with ammonia expected to play a central role at 10 μm, and atmospheric metallicity which probes the formation process. For old and cold RV exoplanets in nearby systems, determining the system's inclination by direct imaging will yield the planet's dynamical mass.

Most excitingly, MICHI's spatial resolution could enable imaging of the first Earth twin in the habitable zone of nearby Sun-like stars. While some Earth-size exoplanets have been found using transit and radial velocity techniques, no Earth-like exoplanets have yet been discovered. Planned NASA missions will not afford this capability; JWST enables limited transit spectroscopy characterization of fortuitously aligned nearby transiting M dwarf systems and WFIRST CGI will likely not reach Earth-mass sensitivity. Far-future (2040+) proposed NASA missions (i.e. HabEx, LUVOIR) rely on detecting exo-Earths in visible/NIR reflected light and hence MICHI's 10 μm coverage affords highly complementary capabilities. TIR imaging is sensitive to planetary emission, where the exoplanet-to-star contrast at 10 μm is 10^3 times more favorable (contrast ratio (CR) requirement $\sim 10^7$) than at visible light (CR requirement $\sim 10^{10}$) for a Sun-like star. Compared to 8 m-class telescopes, TMT is ~200 times more efficient at reaching the required background-limited contrast at 10 μm, requiring <1 hour for a detection of the closest systems instead of 100's of hours using an 8 m. Indeed, the improved Strehl ratio that MICHI (~80%) will enjoy at 10 μm compared that typically obtained on 8 m's (≤30%) will actually make this differential ratio even greater (with the exception of the adaptive secondary mirror (ASM) fed mid-IR (MIR) imager NOMIC on the LBT). The habitable zone is resolved at 10 μm at distance of up to 5 pc for Sun-like stars. Primary northern hemisphere targets include Tau Ceti (multiple candidate rocky habitable zone planets), Epsilon Eridani, and 61 Cygni A/B. TIR imaging of rocky exoplanets promises to significantly enhance the science return of potential future NASA direct imaging missions. Disentangling the effect of an exoplanet's radius from its albedo using only reflected-light spectra is extremely difficult. However, TIR data can constrain the equilibrium temperature of rocky planets and thus the radius. Multi-epoch 10 μm imaging data will help identify optimal observational times for reflected-light space-based observations. Using TMT/MICHI to pre-select the best exo-Earth candidates for spaced-based follow-up could increase the yield for exo-Earth detection by *HabEx/LUVOIR* and could be especially advantageous for missions employing a starshade for spectroscopic follow-up.

TMT's sensitivity enables spectral characterization of the nearest/brightest Earth-like exoplanets (Fig. 1). 10 μm low spectral resolution characterization (calibrated to the star's spectrum) could enable biomarker detection, such as O_3, H_2O, O_2, CH_4 and CO_2, as well as estimates of the planet's surface temperature via blackbody fitting. The transformative science potential enabled by MICHI at high angular resolution and at high contrast far exceed current 8 m class telescopes, and that possible with the 6.5 m JWST.

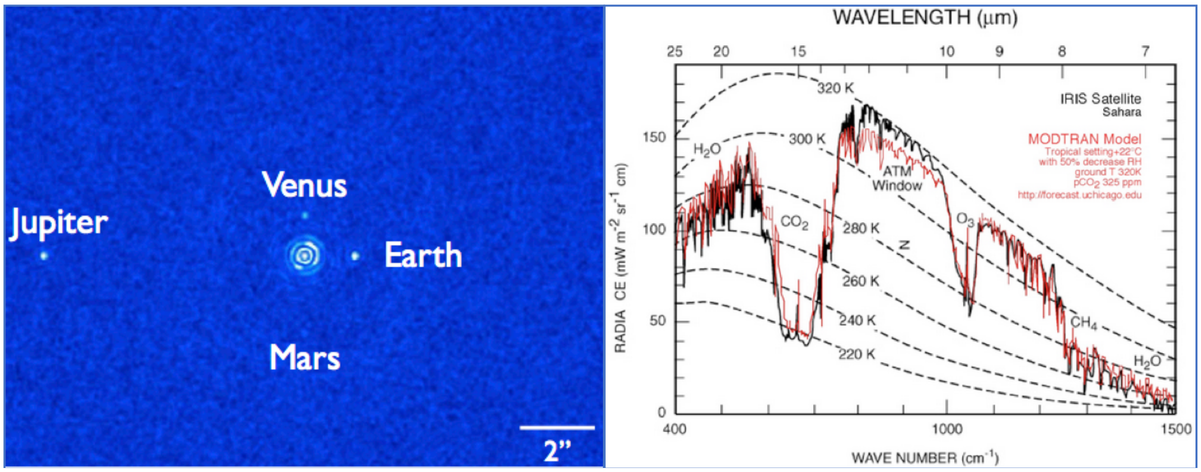

Figure 1. TMT/MICHI 10 μm imaging and characterization capabilities. Left: Simulated image of Alpha Centauri A with MICHI. A coronagraph and advanced post-processing techniques are used to remove the central star (NB. although this object is difficult to observe from Maunakea, it is used as a demonstrator of the concept). Right: Earth N-band spectrum showing various biomarkers in the 10 μm window (adapted from Hanel et al. 1972[3]).

2.2 High Spectral Resolution Spectroscopy of Exoplanets; Detailed Characterization

A TIR high-dispersion spectrometer (HDS) affords high-resolution spectroscopy of exoplanets and offers 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 aspects of their global weather patterns.

MICHI will become TMT's workhorse instrument for estimating atmospheric metallicity through O and C measurements and the ratio of these two elements (C/O). The L band accesses strong H_2O absorption, and this wavelength range has provided the bulk of the high-resolution detections of this molecule in short-period exoplanets (Birkby et al. 2013[4], 2017[5], Lockwood et al. 2014[6], Piskorz et al. 2016[7], 2017[8]). Furthermore, in Solar-abundance atmospheres H_2O is expected to be the most abundant species after H_2 (Heng & Kitzmann, 2017[9]), suggesting that L band measurements of H_2O will form a large part of MICHI's exoplanet work. The L band also hosts the strongest CH_4 feature easily accessible from the ground, a molecule that is yet to be detected in any short-period transiting planet. When L band H_2O and CH_4 measurements are combined with the strong CO and CO_2 absorption lines in the M band, MICHI will be poised to measure the abundances of all major O- and C-bearing molecules; if higher-order hydrocarbons such as C_2H_2 are present, MICHI will also be able to measure their abundance (de Kok et al. 2014[10]), constraining models of hydrocarbon "soot" haze formation in exoplanet atmosphere (Morley et al. 2015[11], Kawashima & Ikoma 2018[12]). Both metallicity and C/O provide strong constraints on the formation method and location of the observed planets (e.g., Mordasini et al. 2016[13]).

One of the most exciting prospects with TMT/MICHI is advancing photon constrained observations of the rotation of exoplanets (Fig. 2), pioneered on the VLT. The β Pic b planet rotation rate of 8.1±1 hours was determined by observations of CO emission lines. Whilst this type of measurement was repeated for ~10 objects, TMT/MICHI will extend this to ~several 10s of objects, enabling a detailed sample of the rotational properties of exoplanets and how they obtained their angular momentum during formation. For numerous highly irradiated planets, detailed line profiles will probe upper atmosphere wind speeds and circulation patterns, advancing high spectral resolution results that previously measured the day-to-night winds speeds on hot Jupiters HD209458 b (-2 ±1 kms^{-1}; Snellen et al. 2010[14]) and HD 189733 b (-1.7 ± 1.2 kms^{-1}; Brogi et al. 2016[15]). Such properties are uniquely determined at high-spectral resolution.

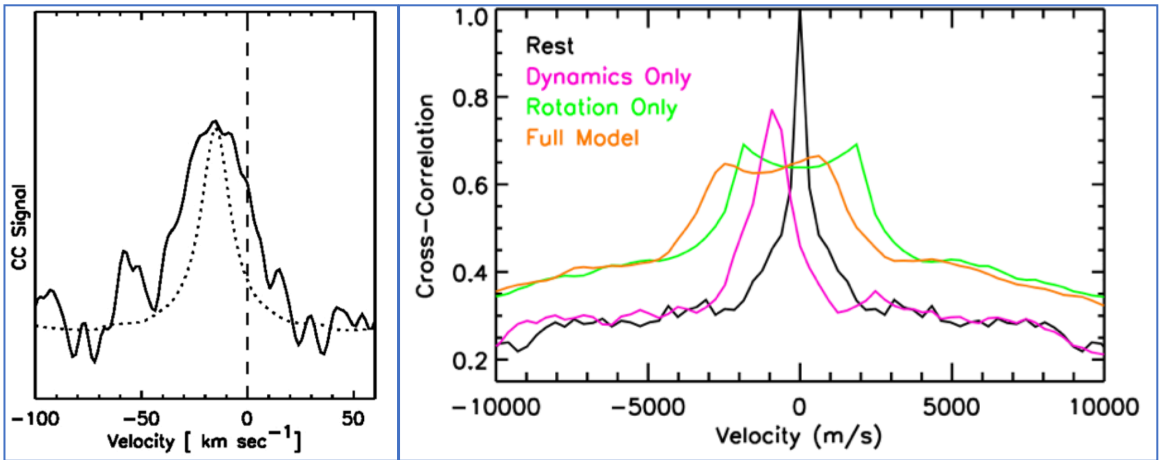

Figure 2. First measurement of an exoplanet rotation (left) showing the rotationally-broadened cross-correlation profile of the giant exoplanet β Pic b (Snellen et al. 2014[16]). The dotted line shows the expected profile without planetary rotation. Examples (right) of the predicted profile of rotation (green line) and winds (purple line) on the cross-correlation profile of exoplanet atmospheres (Kempton & Rauscher 2012[17]; Showman et al. 2013[18]).

More broadly, MICHI high spectral resolution observations will accomplish groundbreaking science on multiple fronts, exemplified by these selected highlights:

- Detect atmospheres of the nearest neighboring rocky worlds via high-dispersion spectroscopy and medium-resolution IFU observations (Snellen et al. 2015[19], Lovis et al. 2017[20], Hoeijmakers et al. 2018[21])
- Detect giant storms on the surfaces of widely-separated giant planets via Doppler imaging (Crossfield 2014[22]);
- Atmospheric chemistry of exoplanets, from (super-)Earths to hot Jupiters, and production of 1D photochemistry maps as a function of longitude. This will lead to the first measurements of low-abundance species, e.g. isotopic ratios connected to evolutionary history (e.g. HDO, 13CO);
- Measure true masses of non-transiting (super-)Earths around nearby bright stars.

3. TIR CHARACTERIZATION OF PROTOPLANETARY DISKS

The prospects for the formation of planetary systems and the development of life are pre-determined in protoplanetary disks. Whether planets have the necessary chemical ingredients to generate and nurture life depends on the chemical and physical disk structures from which they form. Time-dependent theoretical models of the physical and chemical evolution of the disk (e.g. Aikawa et al. 2002[23]) have been tested through observations of disk chemistry and structure (Fig. 3). Particularly the snow lines of water and other volatile molecules (e.g. Blevins et al. 2016[24], Notsu et al. 2017[25]) play a vital role in planetary formation, and subsequently the chances for life. As noted above, such observations are optimally performed at TIR wavelengths due to the greatly improved CR. TMT/MICHI will be capable of spatially and spectrally resolving the snow lines of these species by making use of gas emission lines and ice absorption features (e.g. Honda et al. 2016[26]). Disk thermal structure evolution can also be measured by tracing the spatial distribution of crystalline silicate material in the disk. TMT/MICHI affords a unique opportunity to uncover both mineralogical evolution and transport of solid material within a disk by spatially-resolved MIR spectroscopy (e.g. Okamoto et al. 2004[27], and Fig. 3). For the same reasons as those described in §2, existing 8m's and JWST do not afford the combination of high sensitivity and spatial/spectral resolution, leaving a large and crucial parameter space to be filled by TMT/MICHI.

TMT/MICHI will also be a powerful tool to obtain emission/absorption line profiles of a number of molecular (e.g. CO, OH, H_2O, H_2, CH_4, C_2H_2), atomic (e.g. H lines), and ionic (e.g. [Ne II], [Fe II]) lines in the TIR. Molecular lines are excellent tracers of temperature and abundance, and their spatial location obtained by MICHI will help our understanding of disk chemical/physical structures and evolution (e.g. Salyk et al. 2008[28]; Banzatti et al. 2017[29]). CH_4 and C_2H_2 lines are useful to trace the distribution of the C/O ratio, are only available in the TIR. Atomic and ionic lines in the TIR provide powerful diagnostics of mass inflows, outflows and physical processes (e.g. Neufeld & Hollenbach 1994[30], Pascucci et al 2011[31], Edwards et al. 2013[32], Watson et al. 2016[33]). As multiple processes can produce these lines (e.g. Herczeg et al. 2012[34]) it is critical to have both high spatial (< 0.1") and spectral (R > 60,000) resolution observations to disentangle contributions from infall, accretion, and outflows to assess mass flow rates. JWST/MIRI will not resolve these lines spectrally nor spatially, but TMT/MICHI will. This makes it possible for the first time to audit mass flow rates in protostars & disks, providing fundamental insights into the physical processes that assemble protoplanetary disks.

Growing protoplanets are also important targets to fill in the evolutional gap between the disk and planets. MICHI will be able to detect these objects in two ways with IFU spectral images. First, spiral waves created by accreting planets should be detectable in CO and other molecules (Regaly et al. 2015[35]). Second, a growing giant planet may have a circumplanetary/proto-lunar disk, with a chemical and physical structure analogous to the much larger parent circumstellar disk. Evidence for a planet has already been seen in CO spectroastrometry in a ~10 AU planet around HD 100546 (Brittain et al. 2014[36]); TMT/MICHI will push these detections to within an AU, where planets are more prevalent.

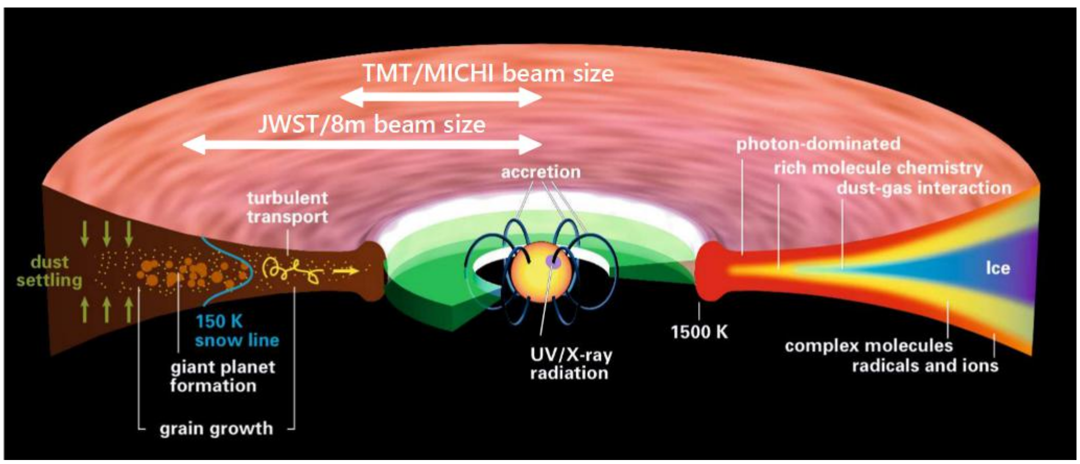

Figure 3. Cartoon of the chemical structure, including the H2O snow line and planet formation in a typical protoplanetary disk around a solar-mass star (adapted from Henning & Semenov 2013[37]).

4. UNRAVELLING AGN & SMBH ASTROPHYSICS

It is observationally well known that supermassive black holes (SMBHs, $\geq 10^6$ $M_\odot$) are ubiquitous in galaxy centers, and the masses of SMBHs and galaxy stellar components are tightly correlated. This suggests that SMBHs and galaxies co-evolved and that SMBHs play an important role in galaxy formation. AGN (active galactic nuclei) are the primary objects in these studies as they are accreting surrounding gas and exchanging gravitational potential energy to produce copious amounts of heat and thermal radiation. The empirically-based Unified Model posits that a central accreting SMBH is surrounded by a geometrically and optically thick torus shaped dusty structure that obscures the central engine from some lines of sight. Although the torus can naturally explain various observational characteristics of AGN, little is constrained about its physical/morphological properties due to its compactness (<10-20 pc, <0.1-0.2" at z> 0.005), nor crucially its interaction with the host galaxy, creation, nor how it is sustained; this is despite the torus being the cornerstone of the theory. The torus re-radiates the central engine's energy, peaking at >30 μm (e.g. Fuller et al. 2016[38]), but detailed MIR properties remain elusive. Recent MIR interferometry (i.e. Hönig et al. 2013[39]) suggests the presence of 'polar dust' at scales of <20 mas, possibly related to feedback mechanisms, further complicating the picture. High spatial resolution observations at TIR wavelengths are the most powerful way to unravel the properties of the enigmatic AGN torus and discriminate it from host galaxy contaminating radiation. Finally, the source of excitation of PAH emission in galaxy centers remains controversial. There are now many objects for which PAH emission is observed within a few 10's pc from the AGN (i.e. Hönig et al. 2010[40]; Esquej et al. 2014[41]) and hence it is unclear if stellar or

AGN photoexcitation is dominantly responsible for the PAH emission. TIR long-slit or IFU observations permit simultaneous probes of the torus, polar dust, and nuclear PAH emission, uniquely available through the combination of high spatial-resolution and high sensitivity that TMT/MICHI offers, unavailable at the spatial resolution of the JWST.

Torus dust emission at TIR wavelengths will be spatially imaged for the first time using TMT/MICHI (Fig. 4, left) for up to ~10 sources. By dramatically reducing host galaxy contamination, high fidelity spectroscopy (Fig 4., right) will be available for ~100 sources, providing a statistically significant sample. This will deliver fundamental information about the size, inclination angle, and dust mass in the torus when combined with existing and under-development models. Such observations will break model degeneracies that pervade current work and allow distinguishing between the plethora of torus models and finally permit a true characterization of the genesis and maintenance of the torus. Observationally it is clear that the torus is geometrically thick but simple torus models gravitationally collapse it to a disk. 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 circumnuclear disk to ~10-20 pc. Others have suggested that the torus genesis and inflation is due to a magneto-hydrodynamic wind (Lopez-Rodriguez et al. 2015[42], Chan & Krolik 2017[43]). 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 (Lopez-Rodriguez et al. 2018[44]), 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. TIR IFU spectroscopy and TMT's spatial and sensitivity gains will allow details of the feedback of material between the host galaxy and AGN central engine to be explored with unprecedented detail, linking the host galaxy to the AGN dominated regions. Detection of nuclear outflows will be compelling evidence of the torus origin by AGN radiation pressure. MICHI will examine the possible link to the large scale (~1-10 kpc) ionized outflows thought to be sweeping material away in the host galaxies. [SIV]10.5 μm and [NeII]12.8μm are key lines due to their high ionization potential. IFU observations with TMT/MICHI in the relatively low extinction wavebands of L and N bands are ideal to address this dichotomy, again impossible at JWST spatial resolution.

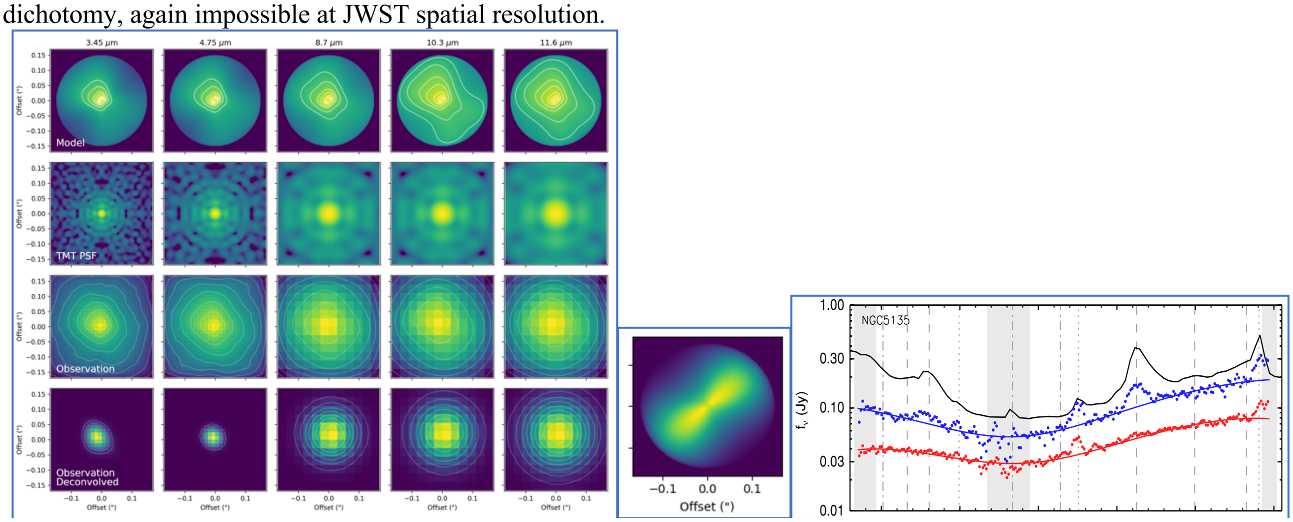

Figure 4. Clumpy model simulation of the torus in NGC1068 (left) at 'infinite' resolution (1st row), the TMT PSF (2nd row), model TMT/MICHI observations (3rd row), and Richardson-Lucy deconvolution (30 iterations, 4th row) showing extended emission along the torus 'funnel' at 3-5μm. Torus model dust distribution is shown (center). The criticality of isolating torus emission from diffuse galaxy contamination is shown for NGC5135 (right, Diaz-Santos et al. 2010[45]). This exemplifies host galaxy contamination in diffraction-limited spectra from Spitzer (0.8m, solid black, galaxy dominated) vs. Gemini (8 m, red = AGN dominated, blue = AGN + nucleus). A similar situation will be repeated in the JWST/TMT era, where JWST data are significantly contaminated, whereas TMT's superior spatial resolution will minimize host galaxy contamination. Definitively resolving the torus (≤10 sources) and minimizing contamination (~100 sources) is essential to advance knowledge of the torus.

5. SUPPLEMENTAL SCIENCE CASES

Our driving science cases summarized in §2-4 provides unique input to the instrument requirements. These requirements permit numerous supplemental projects to be pursued from a variety of fields. Below are two (of the many) exemplary cases our science team has provided.

5.1 The Interstellar Dust Budget Over Cosmic Time

Heavy elements synthesized through stellar evolution have chemically enriched the universe. Massive stars are dominantly the first stellar sources that provided metals and dust in the interstellar medium of galaxies at high-z and in the early universe. Supernovae (SNe) are regarded as excellent candidates for the dust budget in high-z galaxies, but the amount of dust supplied by SNe remains poorly constrained. The paucity of our knowledge of the properties and the geometry of the pre-existing circumstellar medium prevents us from extracting the IR emission from SNe dust and accurately estimating the density and temperature environment of SNe dust. Although JWST will greatly increase the number of observed dusty SNe, the properties of SNe dust will remain poorly determined without knowledge of the circumstellar environment of core-collapse SNe progenitors (e.g., Wolf-Rayet stars and LBVs). TMT/MICHI will resolve circumstellar dust structures around Galactic dusty Wolf-Rayet (WR) stars and LBVs and play a crucial role in understanding how massive stars supply dust into the interstellar medium, particularly in the early universe. Additionally, some recurrent novae (e.g. T Coronae Boreallis, V745 Sco, RS Oph and V445 Pup), whose white dwarf mass is close to the Chandraskhar mass, are regarded as potential progenitors of Type-Ia SNe. With TMT/MICHI, those targets afford an invaluable opportunity to probe circumstellar environment present around Type Ia SNe progenitors.

Galactic novae afford a unique chance to explore dust formation processes in ejecta in 'human-scale' observing timescales. Although novae produce a relatively minor contribution of dust in the interstellar medium, several studies suggest a link between novae dust and pre-solar grains in meteorites. With TMT, expanding ejecta of nearby (< a few kpc) dusty nova are resolvable in the TIR (e.g. Chesneau et al. 2012[46]; Sakon et al. 2016[47]), and combined with LSST optical light curves offer unique opportunities to observe the dust condensation process and possibly to understand the origin of minerals and organics. We note the optical identification of the GW 2017 event and the detection of very heavy element production. As shown by Telesco et al. (2015[48]), TIR at the highest spatial resolution can estimate the mass and element production of SNe. TMT/MICHI will afford the chance to follow-up future novae and GW events to trace detailed element production.

5.2 Solar System Observations

Solar System science will greatly benefit from MICHI on the TMT, as it has with TEXES (e.g. Lacy et al. 2002[47]), mounted on both Gemini North (Greathouse et al. 2011[50]; Tsang et al. 2016[51]) and NASA IRTF, (e.g. Encrenaz et al. 2016[52]; Fletcher et al. 2016[53]). With much higher spectral and spatial resolution than the JWST, MICHI can map temperatures and atmospheric trace species on Mars, Venus, gas giants and their moons, tracking spatial and temporal evolution, to expand our understanding of these diverse worlds, and crucially support data-poor studies of exoplanets. Additionally, with such high spectral resolution TIR capabilities currently unachievable in space, these observations will serve as mission support for NASA and ESA missions (e.g. the Europa Clipper, JUICE (targeted to Ganymede) or Psyche (asteroid belt)).

In 2017 the first known interstellar visitor to the Solar System was identified. "Oumuamua" was observed by numerous telescopes, where the light curve indicated a highly elongated morphology, and the SED implies the presence of surface organic compounds (i.e. Meech et al. 2017[54]). In the LSST era detection of such objects is likely to become common, optimally exploited in the TIR where objects directly radiate. MICHI/TMT will be an outstanding facility to observe their SED, spectra, and light curves of these objects.

6. INSTRUMENT FEASIBILITY

The current (feasibility-level) MICHI design represents an evolution of MIRES, lead by A. Tokunaga and J. Elias. MIRES was a highly optimized MIR (7.5-26 μm) spectrometer, highly leveraged from a MIR adaptive optics (MIRAO) system. Submitted to the TMT Project Office in 2006 in response to the first-light instrument call for proposals, it helped to establish TIR as an important scientific capability for the TMT but was ultimately not selected as a first-light instrument. The TMT SAC feedback concentrated on two key areas, (1) to include a 'blue' 3-5 μm arm and (2) to broaden the capabilities to appeal to a larger TMT community. Several members of the MIRES team are core to the

MICHI team, and through our scientific and technical explorations we have independently converged on a feasibility-level design that comprehensively addresses the SAC points. MIRAO (§6.1) and MICHI (§6.2) designs are (very) briefly introduced below.

6.1 MIRAO Feasibility-Level Design

At TIR wavelengths, AO is required to deliver high-throughput high-Strehl observations whilst keeping thermal emissivity low and system throughput high. Thus, key requirements differ greatly from the first generation NIR TMT AO system, NFIRAOS. The TIR AO system is driven to a simple implementation with no transmissive elements to the science instrument entrance window. At TIR, the implementation of an ASM (adaptive secondary mirror) is an ideal partial solution. We present a short description of a TIR optimized AO system centered around an optical relay and deformable mirror (DM) but that naturally upgrades to use an ASM. Note that the ASM replaces three mirrors in the optical relay – two off-axis parabolas and the deformable mirror; the rest of the AO system, in particular all wavefront sensors and all mechanical interfaces, are still required for the ASM and the instruments it feeds. In the MIRAO concept all of these components are deployed initially with the optical relay and subsequently with the ASM.

The MIRAO design has evolved since the original concept was developed during feasibility studies in 2006 (Chun et al. 2006[55]). The original MIRAO concept assumed a single TIR instrument (e.g. MIRES) working from 7-14 μm, with a goal of 5-28 μm, a small field of view, and that an ASM would not be available at first light but might be a future upgrade path (Fig. 5). A simple optical relay (two off-axis parabolas, a DM, and a single fold mirror) plus a set of three sodium laser-guide star wavefront sensors provides the laser-tomography AO correction (LTAO). Inside MIRES we placed the required natural guide star wavefront sensors (both tip/tilt/focus as well as a place holder for a NIR high-order wavefront sensor should an appropriate detector become available). Provisions for MIRAO's LTAO constellation of LGS are designed into the TMT facility LGS system. With the evolution to MICHI, key science requirements for MIRAO have changed. Of particular note, the required science wavelength is now 3-14 μm with a goal of 3-28 μm and the field of view has increased to up to ~30". Additionally, there is interest in MIRAO feeding multiple science instruments. The original MIRAO concept supports these changes but the relay optics and the order of the AO correction (e.g. the number of actuators) need to be updated accordingly. Progress and the availability of new AO components (e.g. WFS detectors and DMs) makes these changes straight forward. The larger field and shorter wavelengths may require modifications to the LGS asterism but this can be accommodated in the current LGS facility. Details need to be worked out during a future design study.

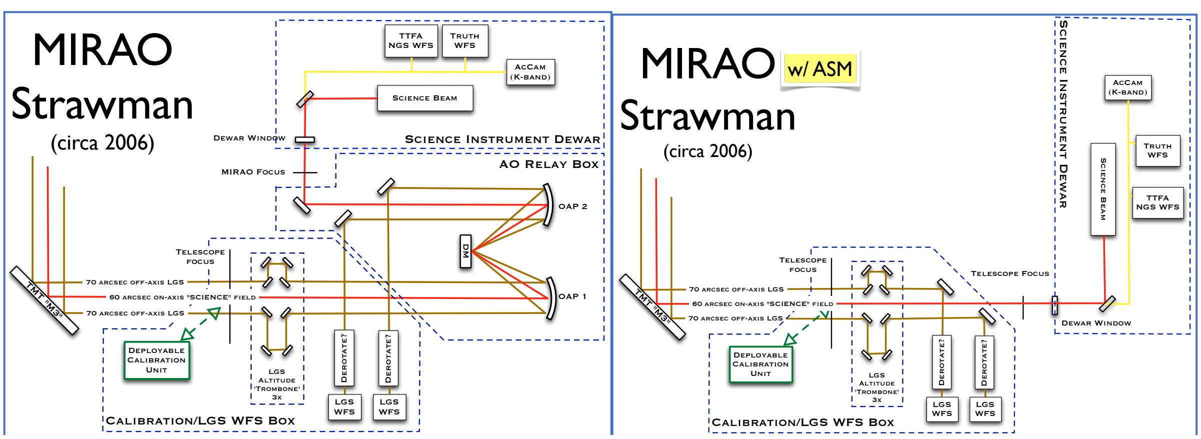

Figure 5. MIRAO schematic design before ASM deployment (left) and after (right).

In several respects our current approach is easier to implement compared to our 2006 study. Advances in NIR detectors and wavefront sensors enable a high-order natural guide star NIR pyramid wavefront sensor for use on brighter science objects while advances in commercially available DMs reduce cost, risk, and size of the pre-ASM MIRAO optical relay. It is now reasonable to implement MIRAO in a phased approach - early science with a low-cost, low-risk natural guide star system followed by an expansion of the science capabilities with a LTAO system that affords increases both sky coverage and science capabilities. An early science version could be built using existing, off-the-shelf technology.

We have also made significant progress on the feasibility of daytime adaptive optics with MIRAO. The motivation is to enable AO-corrected observations at TIR wavelengths during the first 1-2 hours of each morning, before seeing conditions deteriorate. At TIR wavelengths the sky background is dominated by atmosphere and telescope thermal emission and is largely unchanged between day and night. The challenge is how to operate the AO system during the day. If this can be solved, then it opens a path to a 10-20% increase in the available science time on the telescope. Hart et al. (2016) showed that a sodium laser guide star can be imaged through a magneto-optical filter during the day at contrasts similar to night time observations. These extremely narrow bandpass filters effectively suppress all of the daytime sky but have serious engineering considerations for their implementation in a wavefront sensor. Dungee & Chun (2018, in prep.) show that a simpler but broader filter is sufficient if you trade its increased daytime sky background against the number of subapertures in the wavefront sensor. For a system like MIRAO the trade is favorable and results in an AO system that provides good performance at 5-25 μm. These design trades have not been optimized and there are impacts to the wavefront sensor design that need to be considered during the next design phase. Additionally, Dungee & Chun (2018) show that daytime AO observing can also be done with a NIR Pyramid wavefront sensor albeit at a significantly reduced limiting magnitude (K~8). However, at this magnitude there are science targets of interest (e.g. exoplanets and star formation regions).

Finally, we note the high-throughput and simplicity of MIRAO make it well suited to feed other types of instruments. In particular, the high-contrast Planetary Systems Imager (PSI) will require a first stage AO system. We are in close contact with the PSI AO team. MIRAO could be the AO feed for other future TIR instruments that require AO. It is important to ensure that MIRAO meets the requirements of these systems and this will be studied during the design phase.

Table 1. Summary of selected MIRAO optimized requirements.

Requirement	**Value**	**Requirement**	**Value**	**Requirement**	**Value**
Operational λ range	L – Q	Corrected field of view	10" with 1' goal	Wavefront quality	rms phase <350 nm
Sky coverage	"All sky", limited by natural tip-tilt stars	Delivered Strehl ratio	L & M Bands ~60% N & Q Band > 90%		

6.2 MICHI Feasibility-Level Design

In 2008 we evolved the MIRES design to MICHI through (1) enhancing imaging capabilities, (2) adding low-spectral resolution, and (3) adding an IFU, all of which operate at 7.5-26 μm. We also made early investigations of polarimetry and coronography but have not made a final choice regarding their incorporation at the time of this white paper. Work was leveraged from a preliminary optical design using the science requirements at that time. We added feasibility-level discussions of other instrument aspects, documented in a 136p reference document (Okamoto, Packham, & Tokunaga, 2008). From this report, we presented the MICHI design and science cases in SPIE meetings by Okamoto et al. (2008[56]), Tokunaga et al. (2010[57]), and Packham et al. (2012[58]). However, due to a combination of evolving science drivers and technical opportunities, combined with new collaborations, we evolved MICHI to be optimized for 3-14 μm, but are planning to make no technical decision that excludes the Q band (16-25 μm). This scientific choice was dominantly made as (1) the 3-5 μm science cases are more numerous and higher ranked than those in the Q band, (2) the exoplanet community desire for >2 μm capabilities, (3) high-spectral resolution cases are especially strong at 3-5 μm compared to Q-band; technical drivers include (4) the advent of significantly improved TIR detectors at 3-14 μm, (5) the MIRAO 2006 design provides good correction to ~3 μm, and could exploit technical advances for excellent Strehl (~60%) correction to 3 μm, and (6) using immersion gratings from 3-14 μm affords a continuous optical-IR capability to the TMT community.

The instrument is an all-reflective design (except for entrance windows, and possible polarimetric, coronographic, and immersion grating optics, Fig. 6), modular for optimized alignment and/or phased deployment, and compact to fit within the MIRES space envelope. A selection of key instrument requirements used for our design optimization is tabulated below. MICHI dominantly employs off-the-shelf components, with other components in advanced development or characterization phases. The design leverages experience from other similar TIR instruments (i.e. T-ReCS, COMICS, CanariCam, MIMIZUKU, TEXES, EXES, WINERED, VINROUGE, MIRSIS, etc.) of which team members had leading or significant roles in their development, as well as from other on-going projects. The instrument is of relatively low cost and low technical risk. As MICHI is described in detail in the referenced papers, has been presented many times at TMT meetings, on the MICHI web site (https://michi.space.swri.edu), and for space reasons, the interested reader is recommended to those resources for more design information, full team listing, etc.

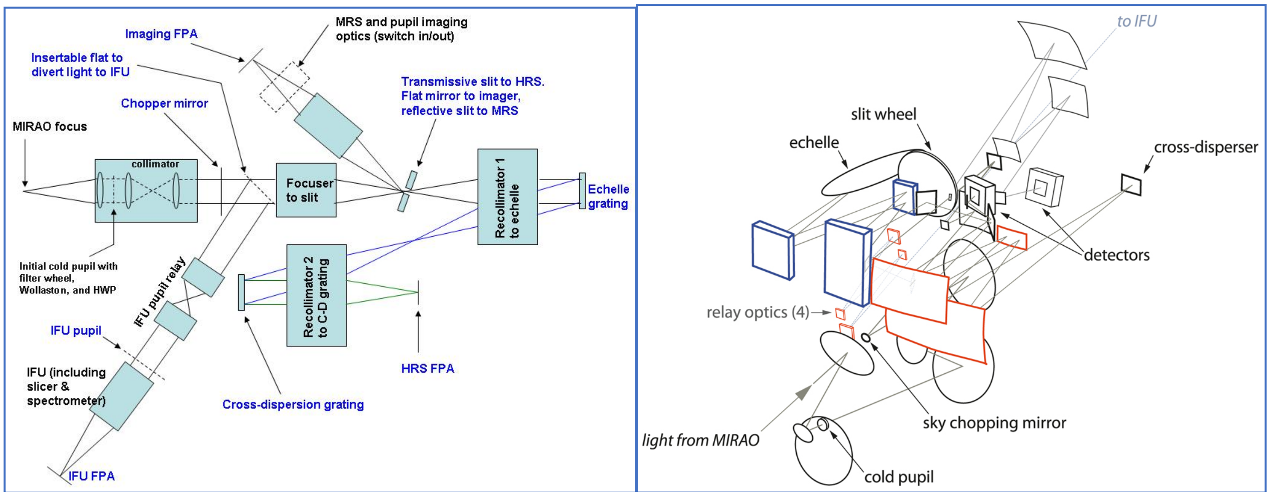

Figure 6. Feasibility-level MICHI design showing the integral modularity (left) and schematic design (right).

Table 2. Summary of selected MICHI optimized requirements.

Requirement	**Value**	**Requirement**	**Value**	**Requirement**	**Value**
Operational λ range	L (3.4-4.1 µm), M (4.6-4.8µm), N (7.3-13.8µm)	Imager field of view	24.4x24.4" at L&M, 28.1x28.1" at N	Imager plate scale	11.9 mas pixel^{-1}at L&M, 27.5 mas pixel^{-1} at N
Long-slit spectrometer plate scale	11.9 mas pixel^{-1}at L&M 27.5 mas pixel^{-1} at N	Long-slit spectrometer resolution	R~600 L, M, & N bands	Long-slit spectrometer slit length	28.1" length
High-res. spectrometer plate scale	11.9 mas pixel^{-1}at L&M 27.5 mas pixel^{-1} at N	High-res. spectrometer resolution	R~120,000 at L&N, R~100,000 at M	Slit length	2" length (but highly dependent on array (see §7)
IFU spectrometer (baseline)	N band (only) 10 spaxels	IFU spectrometer resolution	R~1,000	IFU spectrometer field of view	~0.175" (length) x ~0.07" (width): 35.0 mas per spaxel
Polarimetry (baseline)	L, M, N	Polarimetry modes	Imaging & long-slit spectrometry		

6.3 Synergies With JWST, ELT, & ALMA

Space-based observations at TIR enjoys far superior sensitivity compared to the ground, and the 6.5 m JWST will open completely new vistas, ushering in a revolution in TIR astronomy. It is difficult to conceive of all the new vistas to be opened but TMT/MICHI will be ideal to exploit these observations to the fullest and explore new/independent research areas. JWST spatial resolution will be inferior to that of *existing* ground based TIR capabilities, and inferior to TMT by ~4.6 times (at similar Strehl ratios). Further, JWST spectral resolutions are constrained to a few 10^3, compared to the 10^5 planned for MICHI. Thus TMT/MICHI affords (a) the excellent sensitivity and high spatial resolution (inner working angle) essential for exoplanet direct imaging, disk work, and AGN, and (b) the excellent sensitivity and high spectral/spatial resolution essential for exoplanet atmosphere & disk characterization, offering strong science areas that JWST cannot compete with. To follow-up and fully exploit JWST observations, the combination of sensitivity, spatial & spectral resolution is required. *TMT/MICHI on MKO is arguably the optimal follow-up combination*.

ESO/ELT plans for METIS, a TIR instrument, as one of only three first generation instruments on the ELT. In many respects MICHI and METIS are similar, but with the notable exceptions of METIS not currently planning in their baseline design to offer LTAO capability nor a high-spectral resolution capability in the N band. Further, there are no plans for daytime observing, a capability that seems likely to be possible for MICHI. Despite the differences, there are multiple areas of commonality that can be exploited, as tentatively discussed between the teams, where discussions are leveraged from past and current science and instrument collaborations. For example, we formed a joint array consortium to characterize and purchase new TIR arrays to reduce risk/costs. This affords the possibility to jointly develop read-out electronics, again to reduce risk and/or costs. Collaborations could include common data reduction/interpretation tools, cold chopping mirror, and exchange of knowledge, experience, and personnel especially during assembly, integration, and verification (AIV) stages.

Finally, we note the strong connection between TMT/MICHI and ALMA. ALMA's similar spatial resolution with TMT/MICHI ensures their synergy of wavelength coverage, and an ALMA/MICHI combination will be especially powerful for the science cases discussed above. Specifically, in the case of disks TIR observations provide dust composition information (e.g. PAHs, silicates, H_2O ices) through IR solid state features unavailable from ALMA. For AGN, while ALMA can probe molecular gas and cool dust in the outer torus, TMT/MICHI is indispensable to understand hot/warm dust in the inner torus, polar dust, and outflowing ionized gas (evidence of AGN feedback) with a similar spatial resolution (0.02-0.03"), providing a complete picture of physics around a mass-accreting SMBH in an AGN.

7. CONCLUSIONS

The revolution that JWST will engender, in concert with ALMA, make TIR follow-up from the TMT at high-spatial and/or -spectral resolution essential. The science areas we highlight in this WP exemplify the transformative and broad use cases of MICHI. The team has been working together for several years, evolving instrument drivers in-line with science advances. The science and instrument teams have members from all TMT community countries, is experienced, and are ready to progress MICHI to a fully-fledged second-generation TMT instrument.

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