The Science Drivers for a Mid-Infrared Instrument for the TMT

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ABSTRACT

A mid-infrared (MIR) imager and spectrometer is being investigated for possible consideration for construction in the early operation of the Thirty Meter Telescope (TMT). Combined with adaptive optics for the MIR, the instrument will afford 15 times higher sensitivity (0.1mJy as 5 sigma detection in 1hour integration in the N-band imaging) and 4 times better spatial resolution (0.08") at 10μm compared to 8m-class telescopes. In addition, its large light-gathering power allows high-dispersion spectroscopy in the MIR that will be unrivaled by any other facility. We, a collaborating team of Japanese and US MIR astronomers, have carefully considered the science drivers for the TMT MIR instrument. Such an instrument would offer both broad and potentially transformative science. Furthering the science cases for the MIRES[1], where high-dispersion spectroscopy was emphasized, we discuss additional capabilities for the instrument drawn from the enlarged science cases. The science cases include broader areas of astronomical fields: star and planet formation, solar system bodies, evolved stars, interstellar medium (ISM), extragalaxies, and cosmology. Based on these science drivers, essential instrument capabilities and key enhancement are discussed (see the companion paper Tokunaga et al. 2010[2]): specifically imaging, low- and high-spectral resolution modes, integral field spectroscopy, and polarimetry.

Keywords: Thirty Meter Telescope (TMT), Infrared, Camera, Spectrograph, Image Slicer, Polarimetry

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1. INTRODUCTION

The Thirty-Meter Telescope (TMT)[3] is a next-generation ground-based telescope with a 30 m diameter. It has large light-gathering power and enables high diffraction-limited spatial resolutions with suitable adaptive optics (AO). In the mid-infrared (MIR) region, it will afford the TMT 15 times higher sensitivity than the current ground-based 8m class telescopes and 0.08" (as FWHM of PSF at 10μm wavelength) to 0.16" (at 20μm) spatial resolution with a suitable MIR AO system. In addition, it opens a new window of high-dispersion ($R \sim 10^5$) spectroscopy, which have thus far been rarely observed in the MIR[4]. Elias et al. (2006)[1] studied science drivers for a high spectral resolution TMT MIR instrument. They focused primarily on planet formation revealed by warm gas disk observations with the high-dispersion spectroscopy.

Recently, we, a collaborating group of MIR astronomers in Japan and the US, have further studied the science drivers in more varied astronomical fields. We found that the MIR capability on the TMT is essential to make progress in the science fields of such as planet formation, solar system objects, lifecycle of materials in the universe, blackholes and star formation activity in extragalaxies, and even cosmology. Based on these studies, we re-investigated the required MIR capabilities and instrument design of a MIR instrument on the TMT, or Mid-Infrared Camera, High-disperser, and Integral field unit (MICHI). In this paper, we summarise our key science drivers and required instrument specifications. The instrument design is described in a companion paper by Tokunaga et al. (2010)[2].

2. ADVANTAGES OF MICHI ON THE TMT

Since the TMT is a general-purpose telescope and the instrument would be prepared on the Nasmyth focus stage, the MIR instrument can be relatively large and have various capabilities such as camera, spectrometer of low- to high- dispersion (with a long-slit or a integral field unit), and polarimetry. Combined with the suitable AO system, diffraction limited spatial resolution can be achieved and thus ~15 times better sensitivity than the ground-based 8m class telescopes. Initially we summarize the key advantages of MICHI on the TMT compared to other future facilities.

In the era of TMT, two major MIR space missions will be operational: JWST[5] and SPICA[6]. JWST has 6.5 m diameter primary mirror of $\sim$ 80 K and will use MIRI for MIR observations. It covers 5 to 28μm with R ~3000 and spatial resolution of diffraction-limited value (~0.4" at 10μm), similar to those of ground-based 8m class telescopes. However the sensitivity afforded by JWST is several orders of magnitude better than 8m class ground-based observatories. SPICA is a cooled telescope with 3.5 m diameter primary and is optimized for the MIR. The spatial resolution is ~1" but it will have camera and moderate- and high-dispersion spectrometer onboard, with similar sensitivity to the JWST.

Compared to these future space facilities, a TMT MIR instrument can offer the critical advantages of high spatial resolution and/or high-dispersion spectroscopy. The spatial resolution is 5 to 10 times better which can be of crucial importance for observations of compact objects such as circumstellar disks and galactic nuclei. The future space facilities will find e.g. many interesting disks and features/lines through total fluxes and/or spectra but the spatial structure of the disks is hard to be probed. The advantage of superior spatial resolution can be exploited for all of MICHI's observing modes. In this context, integral field spectroscopy on the TMT is also valuable to resolve compact but extended objects and study their spatial distributions. In addition, space-based facilities are very limited in instrument size and weight, and a high-dispersion spectroscopic capability is difficult to be offered. Although the SPICA will have relatively high-dispersion (R ~30,000) spectrometer, it mainly covers wavelengths that cannot be observed from the ground. Since the ground-based observations are limited within the atmospheric windows, collaboration between the TMT and SPICA provides powerful line studies. In addition, TMT/MICHI has much higher-dispersion (R ~100,000, or $\Delta v \sim 3\mathrm{km\,s^{-1}}$), which is essential to study gas kinematics in the disks through line velocity profiles when compared to e.g. Kepler velocity at Earth and Jupiter orbits that are 30 and 13$\mathrm{km\,s^{-1}}$, respectively. Furthermore, polarimetric capability on the TMT would provide unique observations. Although the polarimetric observations are photon-hungry, space-based facilities will not have such capabilities, due to the reduction in moving components in space-based missions.

From the ground, MIR interferometers with large telescopes such as VLTI[7] and LBTI[8] would be working. In particular, MATISSE on the VLTI has long baseline up to 200 m which enables 0.01" spatial resolution at 10μm under $R \sim 30$ and 100-300 spectral resolutions[9]. The instrument would provide the best spatial resolution at the time, but it has disadvantage of less uv plane coverage. TMT/MICHI has a great advantage in this point that it can reconstruct images with ideal uv coverage. It enables probing 0.08" or even finer scale structures with usual and resolution-improved techniques like spectroastrometry and deconvolution. Also sensitivity is much better for the TMT/MICHI than the interferometers thanks to its large aperture. Thus, the TMT/MICHI is still important for high-spatial resolution science drivers and has complementary role with the ground-based interferometers.

Other 30m-class telescopes are also investigating operation of MIR instruments. The E-ELT is investigating METIS[10], and the GMT is planning for an instrument called MIISE[11]. We note that the site selection of Mauna Kea in Hawaii will be of particular importance for MIR observations.

To summarize, the combination of the spatial and/or spectral resolution and the relatively high sensitivity of TMT is essential and covers unique parameter space which cannot be covered by the future space facilities and ground-based interferometers.

3. TMT MID-INFRARED SCIENCE CASES

MIR observing capabilities on the TMT offer great advantages in many astronomical fields. Among them, we found that three major topics are especially key science drivers of MICHI: planet formation revealed through circumstellar disks, early evolution of the universe through extragalactic activities and cosmology, and lifecycle of materials in the universe. Here we describe these key drivers in detail.

3.1 PLANET FORMATION: OBSERVATIONS OF CIRCUMSTELLAR DISKS

Studies of exoplanets have bloomed over the last 15 years. More than 400 exoplanet candidates in more than 300 systems have been found by various methods, and we now know that there are exoplanets of wide variety: from those largely different from solar system planets (e.g. hot Jupiters and eccentric planets) to those relatively similar. Recently, even direct images of exoplanet candidates have been published and such direct detection is expected for many candidates in the near future. These discoveries raise a number of questions. How are these, and our own solar system, formed? Is our solar system common, or rather unique in our Galaxy? Do habitable expolanets exist and do the host life?

Key observations to answer these questions are those to understand the forming/formed planetary systems. Planets are believed to form in circumstellar disks, which are ubiquitous toward pre-main sequence stars. In the disks, grains must grow from interstellar submicron size to terrestrial planet size of several thousands kilometers, and gas dissipates through accumulation onto giant planets and so on. Material evolution in the disks are related to rich chemistry which might supply seed materials of possible life on the exoplanets. Theoretical models are proposed for some of the key processes of disk evolution related to planet formation while observational test for most of them have just started with recent facilities and most processes are not understood well yet.

MIR capabilities on the TMT are very powerful to reveal the dust and gas processes in the disks. Since the central star is not much brighter than the disks, we do not need coronagraphic masks which shields the information of the most central regions of planet formation. Warm emission of 100 to several hundreds Kelvin from gas and dust of the inner disk region, corresponding to planet forming region, can be probed in the MIR. The wavelength range is rich in dust features and warm organic molecules, too. The diffraction limited spatial resolution resolve the disks with 1 to 10 AU scale for nearby debris disks (several tens parsecs) and protoplanetary disks ($\sim$150pc). It enables us to probe phenomena occurring at planet forming radii directly.

3.1.1 Disk gas

MICHI will provide an unparalleled capability to study gas in the inner planet-formation regions ($<$10 AU) of protoplanetary disks, enabling studies of chemistry, thermal structure, dynamics and evolution of the gas content in disks. Spectroscopic observations with MICHI will be used to address some key issues in the formation of planets and on the origin of water and organic molecules.

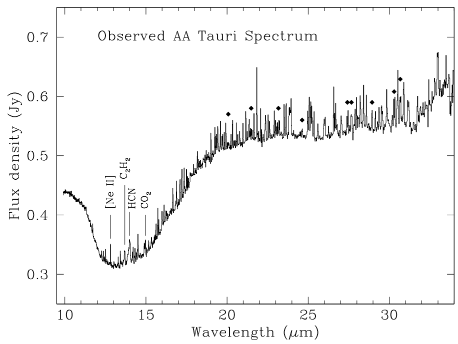

Figure 1. Protoplanetary disks have a rich spectrum of gas diagnostics in the spectral region covered by MICHI. This Spitzer IRS spectrum of the young star AA Tauri[12] shows a forest of emission lines dominated by rotational lines of H_2O, along with transitions of OH (diamonds) and the Q-branches of the organic molecules C_2H_2, HCN, and CO_2. Nearly all transitions are blended at this spectral resolution.

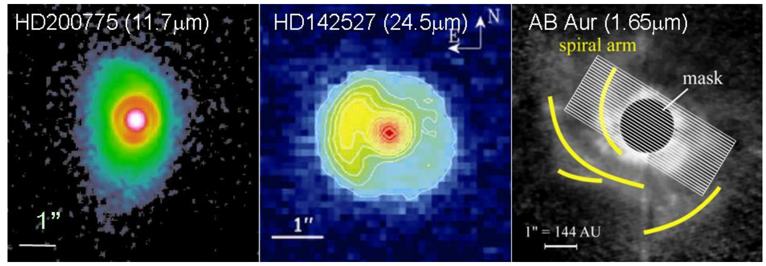

Figure 2. MIR and NIR Extended disks observed with the 8m Subaru Telescope (HD200775[13], HD142527[14], and AB Aur[15]). On the NIR image of AB Aur, MICHI's temporary IFU configuration is overlaid. These disks are largely extended, while MICHI will resolve many smaller disks, too.

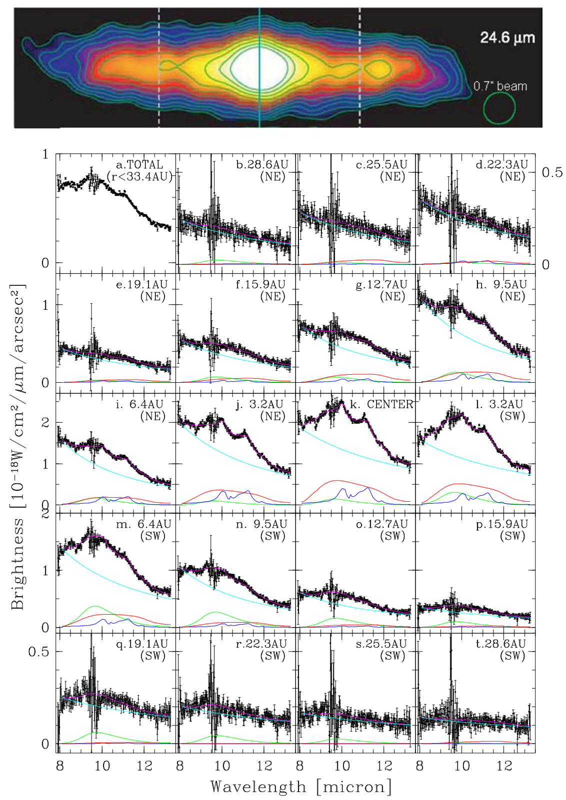

Figure 3. *(Top)* Image of a debris disk β Pic[21]. Asymmetric structures such as warps and knotws are seen in higher-spatial resolution. *(Bottom)* Spatially resolved N-band spectra of the disk of β Pic[22]. It reveals that the silicate dust has different distributribution according to size and crystallinity, which probably corresponds to 'planetesimal belts' and infall motion of grains in the system. MICHI will resolve many disks with spatially-resolved spectroscopy.

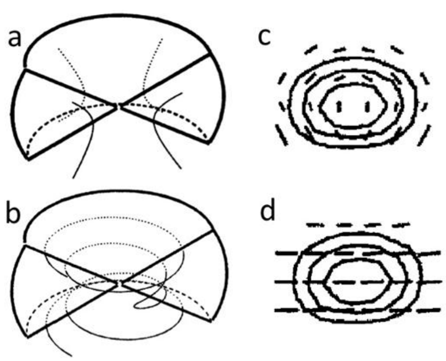

Figure 4. Two examples of B-field configurations in disks and the resultant polarization at $10\mu m$[27] for a disk orientation of 25^o (where 0^o is edge-on) to the line of sight. Panel a illustrates a pinched axial ("hourglass") B-field, and Panel c shows the resultant polarization (typically 3%) morphology. Panel b shows a pinched and strongly twisted field, with the resultant polarization (typically 10%) indicated in Panel d. See Aitken et al. (2002)[27] for more examples.

One of the exciting discoveries from the Spitzer space telescope was the fact that protoplanetary disks can have a rich spectrum of lines in the mid-infrared. As illustrated in Fig. 1, the spectrum of a typical T Tauri star shows a forest of molecular emission lines. This spectrum is dominated by pure rotational lines of H_2O and OH. Emission bands from the simple organic molecules HCN, C_2H_2 and CO_2 are commonly present. The analyses of these and similar Spitzer IRS spectra reveal that the emission is from gas at several 100 K within a few AU of the star, with high abundances of water and simple organic molecules[12]. However, only global properties of the gas can be determined with low-resolution spectra such as these, because of severe line blending and the lack of information on gas kinematics.

The high-spectral resolution and sensitivity of MICHI will unlock the power of these mid-infrared gas diagnostics. The ability to obtain velocity-resolved line profiles will be a major step. With line profiles, the Keplerian rotation of disks can be used to map velocity to radius and derive the radial variation of the line intensity. The broad wavelength grasp of MICHI will provide velocity-resolved spectra for a large number of transitions from multiple molecules, which spectra for a large number of transitions from multiple molecules, which will allow the determination of gas temperatures, densities and molecular abundances as a function of radius. High dispersion coupled with high sensitivity also enables the measurement of very weak spectral features (e.g., rarer molecular species) that cannot be measured at low-spectral resolution because of spectral crowding. With current spectrographs on 8m-class telescopes, measurements are limited to pilot studies of a few strong lines in the brightest objects. The 2-4 orders of magnitude increase in speed of MICHI will transform this research area by making routine detailed studies of the gas properties in the inner disk.

The chemical composition of disks provide clues not only to the chemical processes that operate but also to many of the physical processes that are considered important in the formation of planetary systems. A prime example that MICHI can help to disentangle is the distribution and evolution of water in disks, which is critical for understanding the origin of water on Earth and other inner Solar System bodies. Outside of the "snow line" at a few AU, water condensed as ice can have a major effect on the buildup of cores of giant planets. Inside of the "snow line", water vapor controls the oxidation state and chemistry of gas and the mineralogy of solids. The distribution of water as gas and ice depends on various processes, including radial mixing and diffusion, the migration of small icy bodies, and the growth of large bodies. Velocity-resolved spectroscopy with MICHI of large samples of disks will allow us to understand how water vapor is distributed and how it evolves with evolutionary state of the disk.

An important issue in astrobiology is the possibility of an extraterrestrial origin for the prebiotic molecules that led to life on Earth. Hence, it is important to understand the degree to which organic molecules can be either formed or preserved within protoplanetary disks. High-resolution spectroscopy with MICHI will be an essential tool for investigating the inventory and content of organic molecules in disks. Most simple and complex hydrocarbon compounds have strong MIR transitions, and a majority of these are accessible to ground-based observations. Both high-spectral resolution and high sensitivity are essential in searching for rarer molecular species because of line crowding and the weakness of lines for complex molecules with low abundances.

A complete description of the science cases for MIR high-spectral resolution spectroscopy is given by Elias et al. (2006)[1].

3.1.2 Disk dust

Protoplanetary disks Dust plays important roles in planet formation processes, such as through accumulation and evolution of materials, contribution to disk heating, and so on. In particular, at late stages of disk evolution, decoupling of gas and dust proceeds, and thus it is crucial to understand properties, evolution and processes of dust for understanding planet formation.

In protoplanetary disks, thermal emission from dust reflects the temperature distribution of the disks. The temperature distribution is determined by accretion heating in active disks while by stellar irradiation of dust and conduction to gas due to photoelectric heating in passive disks. It affects disk properties, which are conditions for the planet formation. For example, distribution of ice dust, which is important to increase grain growth efficiency through its high adhesibility, is strongly dependent on the temperature distribution. Since the MIR is sensitive to warm dust emission (~100 to a few hundred K), MIR imaging by MICHI will strongly constrain the size of the warm disk region. In the case of the 8m Subaru telescope, only limited number of disks are resolved[13−15] (Fig. 2). Based on our observations, extension down to one fifth size of diffraction limit (0.016" at 10μm in the case of MICHI) is detectable by radial profile comparison with PSFs. With TMT/MICHI, many more disks will be resolved, since theoretical models predict that the warm regions of disks around Herbig Ae/Be stars (HAEBEs; pre-main sequence intermediate-mass stars with disks) have a few to several tens AU radius according to height[16], for example. More solar-like systems such as T Tauri stars can be probed, too. Such observations are important to test the theoretical models of the disks. Here, not only 10μm imaging but also

20μm imaging will be important, since the thermal emission size is very roughly expected to be $\propto \lambda^2$ while the spatial resolution is $\propto \lambda$. TMT/MICHI has an advantage that it will be constructed at Mauna Kea, which is an outstanding site for 20μm region observations.

MIR imaging with MICHI is also useful to detect disk structures formed through planet formation. After protoplanets are formed, gas and dust efficiently accumulate onto it and can form disk structures such as radial gaps and holes. These will be readily detectable through dust thermal emission. As mentioned above, the HAEBE disks resolved with current 8m class telescopes are very limited. It is partly due to the marginal spatial resolution of 8m telescopes and partly due to the fact that, for disks with continuous distribution from dust-evaporation radius to outer region, emission from the most inner region where the brightness is expected to be dominant affects the measured FWHM size of MIR emission under insufficient (or marginal) spatial resolution. Nevertheless, the resolved disks have radius of ∼0.1" (∼10AU) to >1" (>∼100AU) in extreme cases such as HD142527[14] and AB Aur[17] (Fig.3). It is expected that such extreme disks have large inner holes and thus the inner wall irradiated efficiently by stars illuminates at the MIR brightly. Such holes might be formed by possible growing planets. In the case of HD142527 and AB Aur, MIR emission suggests both of inner disk and outer ring (or wall of outer disk). MICHI is important to detect such structures (outer and even inner structures), probably related to forming planets closely.

To consider more detailed processes, dust grains must grow from ISM size to km-size planetesimals and size of terrestrial planets or cores of giant gas planets (a few thousand km) in protoplanetry disks. In addition, it is predicted that dust grains will settle down to the midplane and decouple from the gas component. To understand how/where these processes occur in the disks is important to understand how and to which stage the planet formation proceeds in the disks. To reveal these processes observationally, we must know spatial (both radial and vertical) distribution of dust grains of various properties (size, composition, etc.). MIR spectroscopy with high-spatial resolution is extremely valuable for this purpose since there are many dust features in the MIR range. The silicate grains have spectral features that differ according to composition, size, shape, and crystallinity. Their features are well studied toward the disks[18], but their spatial distribution is not measured in most cases yet. Their radial distribution will show how/where the dust processes such as grain growth, thermal annealing, etc. occur in the disks. PAH grains also have prominent spectral features in the MIR range and their peak, shape, band-strength-ratio are dependent on the ionization status, size, and shape, thus, on PAH evolution, irradiation by stars, and electron density in result[19]. The evolution of carbonaceous dust in disks are understood little so far. With 8m class telescopes, some HAEBE disks show spatial variation of PAH features[20], and it probably corresponds to PAH evolution and disk environment. MICHI would be powerful to understand the details of evolution of carbonaceous dust and related disk environment.

Since more disks will be resolved with TMT/MICHI, from edge-on disks to pole-on disks, integral field unit (IFU) spectroscopy with low-dispersion (R∼250–500) will be effective for understanding spatial distribution of dust grains. Since planet formation occurs locally in the disks (that is, non-axissymmetrically) and many assymmetric structures such as spiral arms, gaps, and warps are formed[14,15,21] (see Fig.3 for examples), obtaining two-dimmensional information of disks is essential and transformative on the TMT. In this context, IFU spectroscopy is powerful, because it covers the whole disk at once keeping spatial information, and minimizing valuable observing time on the TMT. Although the JWST/MIRI has IFU capability, it does not resolve the disks with its limited diffraction sizes, so MICHI's IFU essentially offers key spatially resolved observations of the disks.

Debris disks In the later stage of planet formation, disk gas dissipates and a disk will become a debris disk. The grains of a debris disk are considered to be replenished from small bodies such as comets and planetesimals already formed in the disk. The disk might have planets, too. In such a gasless system, distribution of dust grains and natal small bodies would be affected kinematically by possible planets which are dominant large bodies in the system and by gravity and radiation pressure by the central star. In particular, dust grains distributed in resonant orbits with the possible giant planets can form fine structure of disks such as rings, knots, gaps, and warps. High-spatial resolution MICHI imaging is powerful to reveal these fine structures of dust distribution formed in nearby debris disks[21]. Shapes of the detected structures have information on mass, orbit, eccentricity of hidden planets and resonance orbit of natal small bodies. Although ALMA will make similar observations in the radio wavelengths, the radio and MIR trace different grain size. Since the behaviour of dust grains depends on the size and composition of dust, both observations are complementary to each other to understand the whole planetary system.

Furthermore, MIR spectroscopy with high-spatial resolution brings much more information on debris disks with dust features[22] Firstly, the size and composition of dust is identified. It allows us to understand behaviour of the dust grains in the disks and thus to understand the distribution of bodies replenishing dust grains more precisely. For example, Okamoto et al. (2004)[22] revealed existence of planestimal belts and possible orbit of a hidden planet in the debris disk around β Pic from its silicate distribution (Fig. 3). The second advantage is that we can estimate the properties of natal bodies from replenished dust propeties. Okamoto et al. (2004) revealed that the most of replenished dust grains in well-known debris disk of β Pic is amorphous silicate grains while the grains that have fell toward the disk center are annealed to crystalline grains by stellar radiation. The information tells us that the natal bodies might be rather undifferentiated. If much more annelead grains were detected in replenished dust component instead, it suggested that the small bodies might be differentiated in larger bodies like protoplanets where heat generation was enough in their interiors, and then broken into small bodies. Such information can constrain the size of small bodies replenishing dust grains and their possible natal planets. Spectroscopy with TMT/MICHI is a powerful tool to understand the whole planetary system. Again, integral field spectroscopy is quite effective for this kind of observations.

3.1.3 Magnetic fields

MIR polarimetry will be able to probe the magnetic field in circumstellar disks and envelopes around young stars. It seems highly likely that magnetic fields play a crucial role in star and planet formation through jets, outflow, and angular momentum transport via magnetorotational instability (MRI). Thus far, MIR polarimetry has been conducted mostly towards very bright massive star forming regions, showing that the magnetic field direction tends to be parallel to the disk or disk-like structure of massive YSOs[23].

MIR polarimetry will play a crucial role in defining the strength and morphology of magnetic (B) fields on AU spatial scales in planet-forming disks. No observations currently constrain these studies, yet B-fields are thought to be critical determinants of disk structure and planet evolution. They are coupled directly to the ionized gas and link different Keplerian zones, thereby generating disk turbulence and viscosity, both of which determine the radial and vertical distributions of solid particles entrained by the gas[24]. Resultant formation of clumps of particles then accelerate grain agglomeration and planetesimal formation. Ensembles of dust particles that have been preferentially oriented in the B-fields polarize MIR radiation (through absorption and/or emission), and the resultant polarization indicates the B-field morphology even in disk regions that are opaque in the visible and NIR. As an example, Pudritz & Norman (1986)[25] propose that during gravitational collapse of a protocloud, the B-field is dragged inward along the disk creating an hourglass-shaped field configuration that co-rotates with the disk. The field lines would then be well organized and perpendicular to the disk. In contrast, Uchida & Shibata (1985)[26] propose that the field's initially hourglass morphology is distorted by disk differential rotation, becoming wound or twisted into a configuration with the field lines lying in the plane of the disk. Aitken et al. (2002)[27] have modeled the expected MIR polarization morphology expected for various B-field configurations in disks, as illustrated in Fig. 4.

To gauge the scale of candidate objects, we use the Herbig Ae/Be star AB Aur[28], at a distance of 144 pc and with a MIR emitting disk radius of $\sim$300 AU. TMT's angular resolution at 10μm will be 0.08", corresponding to $\sim$10 AU. Thus the disk radius will have $\sim$30 resolution elements, and is thus well resolved. The Aitken models show significant differences between the two B-field morphologies and the resultant polarization structures. Thus, we should be able to readily distinguish these configurations if AB Aur had the same tilt to the line of sight as the model disk of Aitken. MICHI polarimetry will be a powerful probe to discriminate between these and other configurations, impossible on current telescopes/instruments. Further, the TMT's collecting area enables us to trace the magnetic field direction toward fainter young stars such as low-mass YSOs and edge-on disk systems, as well as penetrating closer to the star itself.

3.2 EXTRAGALACTIC ACTIVITIES AND COSMOLOGY

The exquisite resolution and large collection area afforded by the TMT enable extragalactic science cases that can be executed either in a superior manner (due to the higher resolution) and/or synergy with the JWST. We briefly highlight three extragalactic areas that MICHI will enable.

3.2.1 Lensed QSO Studies

The cold dark matter (CDM) scenario for structure formation in the universe has successfully explained a wide variety of observational results on spatial scales $\geq$1 Mpc. However, high-resolution N-body simulations on CDM-based structure formation have highlighted discrepancies with existing observations on the spatial scales <1 Mpc. The most serious issue is that CDM models predict the existence of several hundred dark satellites or "CDM subhalos" (with masses of $10^{7-9}\mathrm{M}_{\odot}$) in a galaxy-sized halo (with $10^{12}\mathrm{M}_{\odot}$), in sharp contrast to the observed number of about twenty Milky Way satellites (the so-called "missing satellites problem"). To clarify this outstanding issue, gravitational lensing offers us an invaluable insight into a halo structure, which works as a lens for a remote source such as a QSO. In particular, flux ratios between quadruple images are a sensitive probe for the mass distribution of a lens. A class of lensed QSOs has anomalous flux ratios, i.e., those hardly reproduced by any lens models with a smooth density distribution and such flux anomalies can be caused by any substructures that reside in a lensing galaxy through either of millilensing by CDM subhalos or microlensing by stellar objects. To distinguish the nature of lens substructures, MIR observations of lensed images and their flux ratios provide four key advantages compared with studies at other wavelengths

- MIR flux is relatively free from extinction effects by intervening dust
- MIR flux is free from microlensing effects. The observed MIR flux essentially originates from the dust torus of a QSO producing near-IR emission at the rest frame, where the torus size is much larger than Einstein radii of stellar objects.
- The inner radius of a dust torus can be quantitatively estimated from the QSO luminosity, based on dust reverberation observations. Then with an available source size for this lensing event, it is possible to place a mass limit on the CDM subhalos.
- MIR flux is observable for both radio-loud and radio-quiet QSOs.

A lensed QSO consists of closely separated images (<0.3"), so the large aperture of TMT is essential to separate and distinguish these images, especially for potentially a large number of small-separation lenses. Also, measuring the accurate flux of faint images with <10 mJy is crucial in setting limits on flux ratios for many QSOs. MICHI will be essential to achieve these requirements, allowing us to obtain diffraction-limited images with a high-quality PSF. 8 m class telescopes have been able to detect only a small, bright subset of QSOs with the flux of several tens mJy (see Fig. 5). Thus, MIR observations of many faint lensed QSOs with MICHI will provide essential insight into CDM substructures in galaxies.

3.2.2 AGN

The fueling of black holes in active galactic nuclei (AGN) is fundamental to the evolution of galaxies. AGN may also play a pivotal role in galaxy formation, and hence understanding AGN is crucial to galaxy evolution models. AGN themselves are largely explained in the context of a unified theory, by which a geometrically and optically thick torus of gas and dust obscures the AGN central engine. 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, and (d) What is the role of nuclear (<100 pc) starbursts in feeding and/or obscuring AGNs? 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.

MICHI observations of high spatial resolution images and low-spectral resolution spectroscopy of AGN and luminous IR galaxies (LIRGs) made in synergy with the JWST are analogous to our recent observations using Gemini to help to fully interpret and place 'in context' Spitzer observations. In both the Spitzer and JWST epochs, only the superior spatial afforded by the largest ground based telescopes observing at the diffraction limit allows the AGN, star formation sites, and diffuse emission to be disentangled from each other. Such observations are crucial to understand the local universe for application to more distant objects. JWST observations will form the foundation stone of understanding galaxy and AGN formation, where black hole and AGN evolution may become evident. However, it is clear that even JWST observations will have contamination from emission from diffuse HII regions, necessitating the use of 30m class telescopes. We note that at z=0.5, the spatial resolution of JWST is 1.5kpc (including galactic star forming rings, etc.), whereas for the TMT the spatial resolution is 330 pc (nuclear dominated). JWST will be an outstanding resource for taking integrated imaging and spectroscopic observations of AGN and galaxies, but only the spatial resolution afforded by the TMT will allow targeted and fine scale investigations of the JWST results.

As an illustration of the type of synergistic work one can perform from 30m ground based telescopes and that of the JWST (factor of 4.6 better resolution), we show a comparison of images and spectra taken from the Spitzer and Gemini (factor of 10 better resolution) at similar wavelengths in Fig. 6[30,31]. Later Diaz-Santos et al. (2010)[32] compared Spitzer (∼600 pc) and T-ReCS (∼60 pc) spectra of NGC3256, showing significantly different results. In this case, silicate absorption around 10μm is essentially only from the southern condensate whereas PAH dominates the nucleus. Only high spatial resolution spectra can exclude the surrounding diffuse emission which can easily confuse and contaminate the spectra, possibly misdiagnosing any present nuclear activity, star forming regions, and the torus parameters.

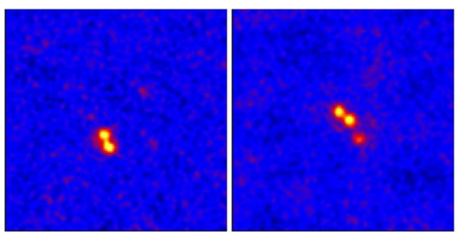

Figure 5. Lensed QSOs PG1115+080 (left) and B1422+231 (right) at 11.7μm using Subaru/COMICS[29].

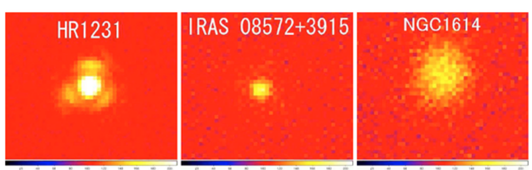

Figure 7. 20μm imaging data. *Left:* Diffraction limited observations of a standard star. *Middle:* ULIRG emission dominated by a spatially-compact source. After PSF subtraction, we can constrain the emission surface brightness to be $> 10^{14}L_\odot kpc^{-2}$ *Right:* Starburst galaxy NGC 1614.

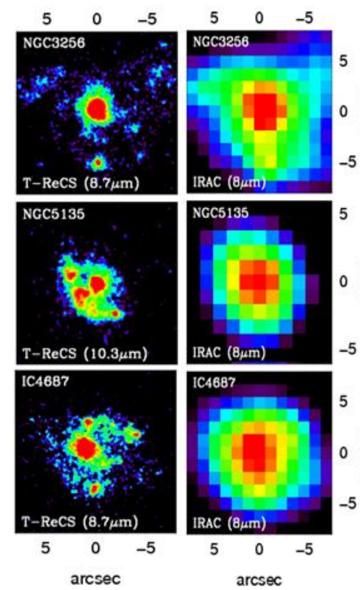

Figure 6. Comparison of AGN images obtained the Gemini/T-ReCS and Spitzer/IRAC.

3.2.3 20μm Observations of ULIRGs

Ultraluminous infrared galaxies (ULIRGs) radiate very large infrared luminosities (LIR $> 10^{12}L_\odot$), suggesting that very powerful energy sources (starbursts or AGNs) are present hidden behind dust. However, the putative AGNs in ULIRGs are deeply buried in gas and dust, and so it is difficult to distinguish from compact starbursts.

One effective way for this distinction is to estimate the emission surface brightness of energy sources. The energy generation efficiency of nuclear fusion inside stars is only ∼0.5% of Mc^2, and the maximum emission surface brightness of a starburst is found to be $\sim 10^{13}L_\odot kpc^{-2}$ both observationally[33] and theoretically[34]. However, the efficiency of a mass accreting AGN is as high as 6-40% of Mc^2 [35], and so an AGN can produce a very high emission surface brightness ($> 10^{13}L_\odot kpc^{-2}$). Therefore, we can determine the presence of energetically important buried AGNs, if the emission surface brightness of the energy sources of ULIRGs are $>> 10^{13}L_\odot kpc^{-2}$.

MICHI 20μm imaging is best suited, because (1) at 20μm, the spatial distribution of dust in thermal equilibrium can be traced, which is the dominant emission component of the ULIRG's luminosity, and (2) the diffraction-limited image size is usually achieved at 20μm (at 8-m class ground-based telescopes) under normal weather conditions (see Fig. 7), making PSFs stable and discussions of spatial extent of infrared emission very reliable. However, due to the limited sensitivity and larger diffraction limited image size ($\sim$0.5") at 20μm with 8m class telescopes, this method has been applicable only to a limited number of ULIRGs. With MICHI's improved spatial resolution and sensitivity, we can systematically investigate the true nature of nearby ULIRGs.

3.3 Life cycle of materials in the Universe

The gas and dust ejected from dying stars are the key to understand the chemical evolution of universe and circulation of materials. Metal elements and dust grains had much lower abundance in the early universe than the present. Metals were synthesized in stellar interiors due to nuclear fusions, were ejected into the interstellar media (ISM) by supernova explosions and mass-loss phenomena of evolved stars such as asymptotic giant branch (AGB) stars, and became materials of dust grains[36]. It has been challenging to measure the actually ejected materials from dying stars to the ISM. There remains disagreements of theoretical predictions and observational results for the amount of ejected dust grains, for example[37]. One of the possible explanation is the underestimation of SN dust and AGB dust, which should be tested using TMT/MICHI. It is an ideal instrument to investigate the quantity of dust formed in dying stars over statistical manner, as well as to investigate the detailed study of individual objects over the dust formation processes.

3.3.1 Understanding dust formation and mass loss from AGB stars

We investigate the formation of dust in AGB in two independent approaches: detailed studies of AGB stars in very nearby solar neighborhood, and statistical study of AGB mass loss over well constrained sample. The current understanding of dust formation around the AGB stars is demonstrated in Fig. 8. The TMT will directly test this hypothesis of spatial structure. AGB stars are pulsating variables, and the pulsations push up materials to the outer part of the atmosphere. The atmosphere is cooler towards the outer radius, and dust grains are formed in the outer part of the extended atmosphere, when gas temperature reduces to about 1000 K[39], which corresponds to several stellar radii[40]. The TMT will be able to spatially resolve the dust-forming region of very nearby stars. For example, we assume the nearby carbon star, IRC+10216, has a stellar radius of 8×10^{13}cm at the distance of 125 pc. If the dust-forming region is at 5 stellar radii, corresponding to 0.2" in radius, it will be resolved by MICHI (0.08" resolution at 10 μm). Indeed, IRC+10216 was resolved at near-infrared, and clumps on this object has a diameter of 325 mas[41] (Fig. 9). Potentially resolved targets include alpha Ori and V Hya. There are many dust features in the MIR range: amorphous silicate (9 and 18 μm), crystalline silicate (12, 17 and 24 μm), corundum (11 μm), and SiC (11 μm). These dust features are spatially resolved in low-resolution spectroscopy with MICHI. ,

The transition region from the photosphere to the dust forming region is called extended atmosphere, or 'molesphere', which is filled with molecules (Fig. 8). These molecules are assumed to be the primarily step for dust formation. Molecules found in this extended atmosphere include H_2O, CO, SiO, and C_2H_2. Different molecular lines trace the different places in the molesphere. Measurements of these molecular lines, using the high-dispersion spectroscopic instrument MICHI, will reveal dynamical motion of gas within this atmosphere, where gas motion is caused by stellar pulsations[42]. The TMT will provide an opportunity to investigate the formation of the molesphere and subsequent dust formation, which causes mass loss from AGB stars.

TMT will test dust processing around the stars. Amongst dust formed around AGB stars is polycyclic aromatic hydrocarbons (PAHs)[43]. They are hardly detected from AGB stars, due to lack of the UV radiation to excite PAHs. Once the stars leave the AGB phase, and the effective temperature increases towards post-AGB and planetary nebula (PN) phases. PAHs are commonly detected from carbon-rich post-AGB stars and PNe. The PAH spectral profiles found in circumstellar envelopes often differ from those found in the HII regions: 11.3 μm intensity with respect to 12.7 μm one is higher in HII region than post-AGB stars[44]. That is usually attributed to dust processing in the ISM and PNe under the harsh UV radiation, and post-AGB stars, which have effective temperature of 5000-10000 K, and mild UV radiation, PAHs could remain as large compounds. If that is the case, PAH spectral profile varies within the single post-AGB stars and PNe. Post-AGB stars should have large compound PAHs in the inner part of the envelope, and smaller ones in the outer part, due to the ISM radiation. The spatial variation of PAH profile is reported in 10μm observations of one post-AGB star, Red

Rectangle[45]. With the current 8-meter telescopes, the spatial resolution and the sensitivity is limited, and wide range of objects (such as NGC 6302, HR 4049, IRAS 21282+5050) can be observed by the TMT to test this hypothesis.

TMT will be able to provide quantitative analysis of dust formed around AGB stars in clusters and nearby galaxies, where age and metallicity of these stars are well constrained than those in the general field. The clusters and nearby galaxies provide laboratory of dust formation at the wide range of metallicities. For example, Sculptor dwarf spheroidal (dSph) galaxy (distance of 79 kpc) has a metallicity of about 20% of the solar value, and NGC 6822, dwarf irregular galaxy at a distance of 497 kpc and the metallicitiy of 50% of the solar, has young populations. Dust formation process at different metallicities (in particular, low metallicities) is important to answer a question if it is possible to form dust in low-metallicity environment at the early universe. Observations of AGB stars in clusters and nearby galaxies requires high angular resolutions to avoid source confusion limit, where the TMT has a large advantage.

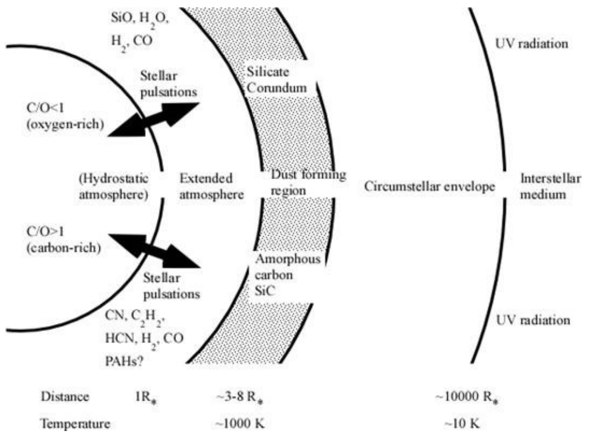

Figure 8. Radial structure of an AGB star (adopted from Fig 1.1 of Habing & Olofsson (2003)[38], which is originally designed by T. Le Bertre.)

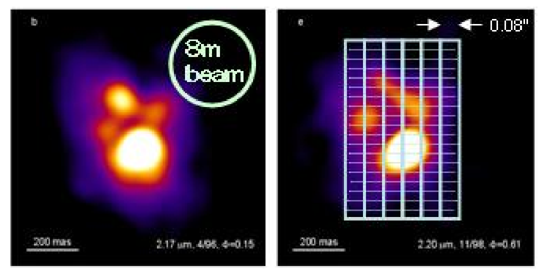

Figure 9. High-resolution bispectrum speckle interferometry images of a carbon-star IRC10216 at different epochs taken from Osterbart et al. (2010)[41]. *(Left)* The FWHM size of the PSF at 10μm of 8m-class telescopes is overlaid. *(Right)* Part of the FOV of the N-band IFU of MICHI is overlaid. The thick and thin lines indicate the slice width (0.08") and pixel size, respectively.

3.3.2 Dust formation/ejection from massive stars

Massive stars play an important role in the chemical evolution of the universe due to their short main-sequence lifetime and the fact that the heaviest elements are formed in their interior and their explosion. Understanding the ejection/formation process of heavy elements and dust by massive stars are crucial to study the chemical evolution in the early universe and dust emission detected in high redshift QSOs at z$\sim$6, where low- to intermediate-mass stars cannot contribute as dust budgets[46].

One of the major formation process of dust by massive stars is the dust condensation in the ejecta of core-collapse supernova (SN) explosions[47,48]. Recent infrared observations of supernova (SN) 2006jc with AKARI and Spitzer, however, have shown that the amount of newly condensed dust in the ejecta of SN2006jc is more than 3 orders of magnitude smaller than theoretically predicted values of $0.1 - 1M_\odot$ [49] but that the significant amount of dust have been condensed in the mass-loss wind associated with Wolf-Rayet stellar activity prior to the SN explosion[50,51].

Several Galactic Wolf-Rayet (WR) WC-class stars in binary systems with O-type stars are known to form dust periodically whenever the O-type companion star comes across the periastron and passes through the densest regioin of the carbon-rich WR wind[52]. WR140 is one of the nearest (d=1.85kpc[53]) and best studied dust making WR stars and the concentric dust clouds formed during every periastron expanding with 0.3"/yr (corresponding to 1600km$\,$s^{-1}) have been resolved in the MIR with *Michelle* on Gemini and *COMICS* on Subaru[54,55]. Several other dust forming WR binaries like WR140 have, so far, been found within a few kpc. The higher spatial resolution and better sensitivity observations of these targets with TMT will play a crucial role in demonstrating the condensation, grain growth and the destruction process of dust around the WR stars in a timescale of a few tens years. Moreover IFU spectroscopy and polarymetry are also indispensable to study the composition and the chemical evolution of the dust around the WR stars and to demonstrate the structural evolution of the dust shells.

MICHI capabilities are powerful also for the study of heavy element synthesis. Supernovae synthesize heavy elements, such as Si, Fe, and Ni during the explosion, and SNe are thought to be the primal source of the heavy elements in the universe. Line profiles of the metals toward SN ejecta is crucial to understand the metal distribution in the nebulae. The MIR observations have advantages of much less line blending and lower optical depth than the optical and the near-infrared. Thanks to them, together with the rapid expansion of the SN ejecta (1000–10000km s^{-1}), a moderate dispersion (R>∼ 500) MIR spectroscopy is the most suitable tool to study birthplace of the heavy elements. Although space observations are basically suitable for this kind of studies, flexible target-of-opportunity observations are essential. It still requires high-sensitivity ground-based facilities strongly, and TMT/MICHI capabilities are really meaningful.

4. REQUIRED CAPABILITES AND SPECIFICATIONS OF MICHI

Based on the science drivers, we summarize important required capabilities for TMT/MICHI as follows.

- The basic capabilities
  - Imaging at the N (7.3-13.5μm) and Q (16-25μm) band regions with field of view (FOV) ∼30"
  - Low-dispersion spectroscopy at the N and Q bands with $R \sim$ a few hundreds
  - High-dispersion spectroscopy at the N and Q bands with $R \sim 10^5$
  - MIR AO system which enables diffraction limit spatial resolution in the N and Q bands
  - Cold internal chopper to enable high-sensitivity imaging and lower dispersion spectroscopy
- The key enhancement
  - Integral field spectroscopic capability with the low-dispersion (R∼250 to 1000) and ∼2"×5" FOV
  - Polarimetry in both imaging and low-dispersion spectroscopy modes

As an instrument to realize these capabilities, we study the instrument MICHI (Mid-Infrared Camera, High-disperser, and IFU) for the TMT. MICHI is composed of the MIR AO system (MIRAO), optics for imager and long-slit spectrometer (MIRES), and IFU spectrometer. The MIRAO and MIRES is based on the previous study of MIRAO/MIRES[56–58] and the IFU part is completely new. We made preliminary design study of MICHI and the detailed results are described in Tokunaga et al. (2010)[2].

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