Studying Galaxy Formation with *SPICA* and Future Extremely Large Telescopes

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ABSTRACT

2020's will be the era of 30–40 m telescope for the ground-based optical and infrared astronomy. These Extremely Large Telescopes (ELTs) have synergy with *SPICA* in studying galaxy formation in the history of the universe. In this presentation, we introduce the planned capabilities of ELTs, focusing on Thirty Meter Telescope (TMT) which Japanese astronomers promote with the international collaboration. We then discuss science cases where TMT and *SPICA* will have complementarity and synergy in the field of galaxy formation and evolution.

1. **2020'S: ERA OF 30–40 M EXTREMELY LARGE TELESCOPES**

Following the great success of the 8–10 m class telescopes including Subaru, VLT, Keck, and Gemini, now ground-based astronomy is moving forward to develop the telescopes with significantly larger aperture, 30–40 m. At this moment, three such projects of Extremely Large Telescopes (ELTs) are being proceeded; Thirty Meter Telescope (TMT[1]), Giant Magellan Telescope (GMT[2]), and European Extremely Large Telescope (E-ELT[3]). These facilities are very powerful tools and will produce the results that bring new insights in many fields of astronomy from extrasolar planets to cosmology. In the past several years, National Astronomical Observatory of Japan (NAOJ) and Japanese astronomers have made the efforts, with the international partners including UC, Caltech, Canada, India, and China, to develop the TMT project. In 2013 June, it was announced that the Japanese government fiscal year budget was allotted to fund a portion of the expenses for the preparation and construction of TMT. The science goals of TMT shall be (i) characterizing extrasolar planets, (ii) studying the earliest galaxy formation beyond Cosmic Reionization, (iii) studying Dark Energy and dark matter, and (iv) providing opportunities of the deepest and the highest-resolution optical and NIR observations. Especially in studying galaxy formation, *SPICA* has complementarity and synergy with the ELTs. In Table 1, we briefly summarize the basic properties of TMT early light phase with those of *SPICA*.

Table 1. A brief comparison of TMT and *SPICA*

	TMT (early light)	*SPICA*
Wavelength coverage	0.3–2.5 μm	5–200 μm
Spatial resolution	10 mas(AO)	0.″5 (at 7 μm)
	0.″5 (NS)	0.″5–10″(at 140 μm)
Instruments	NFIRAOS (AO)	MCS
	IRIS (NIR IFR, imager)	SAFARI
	IRMS (NIR MOS)	FPC-S
	WFOS/MOBIE (optical)	SCI
Field of View	<4″(IRIS,IFU), 16.″4 (imager)	5′ × 5′ (MCS)
	2′ × 2′ (IRMS)	2′ × 2′ (SAFARI)
	5′ × 10′ (MOBIE,TBD)	
spectral resolution	R=4000–8000 (IRIS)	R=2000 (MCS)
	R=4000–10000 (IRMS)	R=2000 (SAFALI)
	R=1000–8000 (MOBIE)	

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[1] http://www.tmt.org/

[2] http://www.gmto.org/

[3] http://www.eso.org/public/teles-instr/e-elt/

Table 2. TMT early light instruments

TMT instruments	description	E-ELT	GMT
NFIRAOS	Narrow-field IR AO System		
IRIS	IR imager and integral field spectrograph	HARMONI MICADO	HRCAM
WFOS-MOBIE	Wide-field multi-object optical spectrograph	OPTIMOS	GMACS
IRMS	IR multi-slit spectrograph and imager		NIRMOS

Table 3. Line up of the second stage instrument proposals

TMT instruments	description	E-ELT	GMT
MICHI	MIR Camera, High-disperser, and IFU		
IRMOS/AGE	Multi-IFU, near-DL, near-IR Spectrometer	EAGLE	
HROS	High Resolution Optical Spectrograph	CODECS	
NIRES	NIR High Dispersion Spectrograph	SIMPLE	
SEIT	Second-Earth Imager for TMT		
PFI	Planet Formation Instrument	EPICS	
MIRES	Mid-IR Echelle Spectrometer and Imager		

There are many fields that *SPICA* has strong synergy with the TMT and its early light instrument. For example, *SPICA* can characterize the star-formation properties of the distant galaxies by their dust emission as well as the redshifted fine structure lines, which can be combined with the internal structure of the galaxies resolved with TMT/IRIS. The field of view of SAFARI matches with that of IRMS. It must be useful to obtain NIR spectra of the SAFARI sources very efficiently. We will discuss some interesting cases in the next section.

Table 2 and 3 summarize the planned early-light (i.e., for a few years from the first light) and future instruments for TMT together with the 'rival' instruments proposed for E-ELT and GMT. At the early light phase, TMT will be equipped with the three instruments, namely, IRIS (AO assisted integral field unit spectrograph and imager), IRMS (AO assisted multi-objects NIR spectrograph), and MOBIE (optical seeing-limited multi-object spectrograph). While TMT as well as its instruments are built for general purposes, the primary science cases with IRIS are; spectroscopy of the galaxies at high redshift beyond the cosmic reionization, studying the internal physical and kinematical properties of forming galaxies, studying the relativistic phenomena near the Black Hole at the Galactic Center, and characterization of extrasolar planets. The MOBIE science cases include mapping of intergalactic medium by using the background galaxy light, detailed spectroscopy of the ultraviolet emission of the high-redshift star-forming galaxies. IRMS is also a very powerful tool to study the redshifted rest-frame optical and ultraviolet spectra of faint galaxies.

More than a few concepts of the instruments which have the capabilities complementary to the early light instruments have been discussed (Table 3). Of these, MICHI, MIR Camera, High-disperser, and IFU, proposed by the international consortium (see Packham, C., this conference) has the great synergy and complementarity with *SPICA* as they observe the common range of wavelength (8–20 μm). It is obvious that the advantage of MICHI is the higher spatial resolution thanks to the 30 m TMT aperture, which provides the diffraction limited image of FWHM$\sim 1''$at 20 μm.

2. TMT AND *SPICA*: COMPLEMENTARITY AND SYNERGY

We here discuss some relevant science cases for which TMT and *SPICA* have complementarity and/or strong synergy.

2.1. Galaxies Beyond the Epoch of Cosmic Reionization

Redshift beyond $z = 8$ is the frontier left for unveiling the earliest galaxy formation in the universe (e.g., Robertson et al. 2010; Ellis et al. 2013). It is one of the primary questions in the modern astronomy to understand when, where, and how the first-generation of stars and galaxies were formed in the early history of the universe, and to reveal how the cosmic reionization occurred. Obviously, the most direct way to answer these questions is to observe the objects in the era and to constrain their physical properties. So far the ultra-violet (UV) emission from the galaxies is observed to $z \sim 8$ and

SPICA and ELTs

Table 4. Expected surface number density per 1 deg^2 of high-redshift galaxies brighter than 28AB mag

redshift	Luminosity Evolution	Semi-Analytic Model	DMH proportional
8–9	1690.	630.	850.
11–12	100.	50.	4.
14–17	0.7	1.	0.003

the Lyα emission from the galaxies at $z = 7.2$ was firmly detected (Shibuya et al. 2012). While it is very likely that the neutral fraction of the universe increases toward $z \sim 6$ and beyond, cosmic reionization may have started before $z \sim 10$ as inferred from the observation of the polarization of Cosmic Microwave Background (CMB) radiation (Komatsu et al. 2009). It is then essential to expand the observations of galaxies beyond $z \sim 8$, toward the redshift well beyond $z = 10$.

TMT will have the great sensitivity compared to the current facilities in spectroscopic observation for a very compact object. In the several hours integration with the spectral resolution of $R = 4000$, the expected signal to noise ratio > 10 per resolution element will be achieved for the galaxies $H \sim 27$ mag at the spectral region between the strong OH atmospheric lines (e.g., Wright et al. 2010). We have estimated the expected number density as a function of the apparent magnitude by extrapolating the UV luminosity function at z =6–8 observed with *HST* toward $z = 15$, and found that the significant number of the objects which are brighter than the TMT sensitivity can be detected by the wide-field deep NIR observations from space; the expected surface number densities of the objects per 1 deg^2 area brighter than 28AB magnitude (at the detection wavelength) is summarized in Table 4 (from *WISH* Mission Proposal Draft, 2012).

If the diffraction limited image at 5 μm is assumed, *SPICA* FPC-S direct imaging mode will have the sensitivity limit of ~28 AB magnitude with ≈ 10 h integration at 2–4 μm. While the field of view of *SPICA* FPC-S, $5' \times 5'$ is not ideal for the purpose, if there is enough amount of time such as in the Parallel Operation or in the Warm Mission Phase, sky coverage of ~ 0.1 deg^2 (that needs 700 hours, assuming 50 hours per field with four filters) yields O(100) of the galaxies at z =8–9, and O(10) galaxies at z =11–12. In this sense, *SPICA* can provide the spectroscopic targets to ELTs. Dedicated survey missions such as *WISH*, however, will produce significantly larger sample for such a purpose.

SPICA, on the other hand, can address the issue by somewhat different approach. First, study of the spectrum of Cosmic Near InfraRed Background (NIRB) and its spatial variation is the primary science case for FPC-S. The unidentified spectral shape, especially the broad peak near 1 μm can be a signature of the earliest star formation in the universe that is not resolved to the individual sources. Spatial variation of the spectra will provide the key information to distinguish such possibilities. Another interesting approach is to observe the Hα emission of the objects at $z > 6.5$ by MCS to constrain their Lyα/Hα ratio. While the 1h sensitivity of MCS is 1–a few $\times 10^{-20}$ W/m^2, the Hα line flux from a $z = 7$ object of 2×10^{-20} W/m^2 corresponds to the Star Formation Rate (SFR) of ~ 100 M$_\odot$/yr. While the volume density of such luminous object is likely to be as small as 10^{-7} Mpc^{-3}, preselection by other facilities such as Subaru HSC, *WISH*, or sub-mm survey telescope is possible. By observing the Lyα/Hα ratio of more than a few objects will constrain the neutral fraction of the hydrogen at such high redshift. Indeed, an object with SFR of 2900 M$_\odot$/yr at $z = 6.34$ was discovered by the HerMES survey with the *Herschel* telescope and the follow-up observations so far.

2.2. Physical Process in Hierarchical Galaxy Formation

SPICA and ELTs should have a great synergy in studying the physical properties of the galaxies in their formation phase. *SPICA* can characterizes the star-formation and AGN activity by their dust emission, and *against* the dust obscuration. Fine structure lines from the H II regions and PDR, PAH emission, and dust thermal continuum emissions are powerful tools to make diagnostics of the high-redshift galaxies, especially the massive galaxies in their early stages of formation with dusty environment. By observing the ratio of the appropriate set of the fine structure lines, one can constrain the hardness of the ionizing radiation (presence of AGN, starburst age, upper mass limit of IMF, metallicity), ionization parameters, electron density. This even allows observing the properties of episodic star formation with relatively short time scale, which enables to draw the whole demography of the galaxy formation phenomena. The expected observed flux of the most ubiquitous [Ne II] and [Ne III] lines from a ULIRG with $L(\mathrm{IR}) \sim 10^{12}$ L$_\odot$ is f([Ne II]+[Ne III]) ~ 8×10^{-19} W/m^2, 1×10^{-19} W/m^2, 5×10^{-20} W/m^2 for the object at $z = 1$, $z = 2$, and $z = 3$, respectively. The expected sensitivity of *SPICA* SAFARI is ≈ 1×10^{-19} W/m^2 (1h, 5σ), we may obtain the *ratio* of the lines from such a ULIRG at $z \sim 1$, and at higher redshift for more luminous objects.

On the other hand, TMT reveals the internal kinematics, structures, resolved properties of the ionized gas (traced by the lines at shorter wavelength), and the stellar population of the high-redshift galaxies. In this sense, TMT and *SPICA* are very much complementary and have strong synergy. By having both the capabilities, we can study the wide range of the phenomena during galaxy formation to understand their physical processes.

As for an example, we introduce the multiple merging galaxies at high redshift as an ideal target for the combined observations with *SPICA* and TMTs. Figure 1 shows the Subaru MOIRCS K-band image of a sub-mm source at $z = 3.1$. Within the error circle, there are six very red objects, which satisfy the color criteria of Distant Red Galaxies ($J - K > 1.4$) or Hyper Extremely Red Galaxies ($J - K > 2.1$). The number density of the DRGs and HEROs is extremely high,

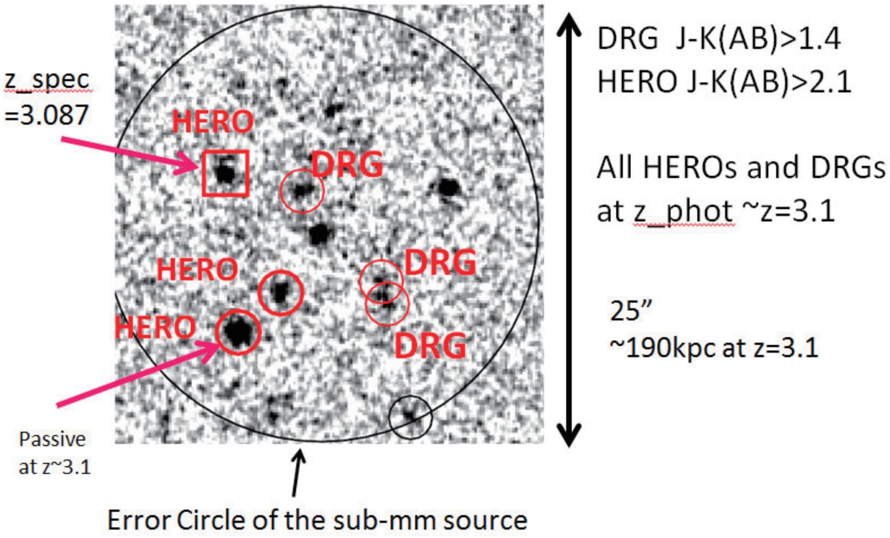

Figure 1. Examples of multiple merging galaxies from Uchimoto et al. (2012). A sub-mm source SSA22-AZTEC-14 is shown in the K-band image. More than a few very red K-band detected galaxies (DRGs and HEROs) are detected in the error circle for the sub-mm source. The number density of the DRGs and HEROs is extremely high, suggesting that they are physically associated with each other at the same redshift.

suggesting that they are physically associated with each other at the same redshift. Some of them are spectroscopically confirmed to be at $z = 3.1$. They are likely to be the mixture of dusty star-forming galaxies and post-starburst quiescent galaxies. *SPICA* SAFARI's extremely deep spectroscopy may simultaneously obtain the spectra of active star-forming galaxies and the diagnostics from the fine structure lines enable us to reveal the presence of AGN or their starburst ages. On the other hand, TMT IRIS or IRMS spectroscopy provides the resolved kinematic information as well as the stellar population. Combining the data obtained by *SPICA* and TMT, we may unveil the whole nature of the very massive galaxies in their early formation phase.

REFERENCES

Ellis, R. S., McLure, R. J., Dunlop, J. S., et al. 2013, ApJL, 763, L7
Komatsu, E., Dunkley, J., Nolta, M. R., et al. 2009, ApJS, 180, 330
Robertson, B. E., Ellis, R. S., Dunlop, J. S., et al. 2010, Nature, 468, 49
Shibuya, T., Kashikawa, N., Ota, K., et al. 2012, ApJ, 752, 114
Uchimoto, Y. K., Yamada, T., Kajisawa, M., et al. 2012, ApJ, 750, 116
Wright, S. A., Barton, E. J., Larkin, J. E., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series (SPIE), vol. 7735, 77357P