SPICA Observations in the Era of Ground-Based THz Astronomy

Hiroyuki Hirashita,[1] Patrick M. Koch,[1] Satoki Matsushita,[1] Masaaki Otsuka,[1] Shigehisa Takakuwa,[1] Yuji Urata,[2] Kuiyun Huang,[1] Satoko Takahashi,[3] Keiichi Asada,[1] Hsian-Hong Chang,[1] Francisca Kemper,[1] Kai-Yang Lin,[1] Yen-Ting Lin,[1] Hauyu B. Liu,[1] Sheng-Yuan Liu,[1] Masanori Nakamura,[1] Sundar Srinivasan,[1] Ya-Wen Tang,[1] An-Li Tsai,[2] Ming-Jye Wang,[1] and Wei-Hao Wang[1]

[1] *Institute of Astronomy and Astrophysics, Academia Sinica, Taiwan*
[2] *Institute of Astronomy, National Central University, Taiwan*
[3] *National Astronomical Observatory of Japan, Japan*

ABSTRACT

When *SPICA* starts observations, some ground-based terahertz (THz) telescopes will be in operation by targeting atmospheric windows around 1–1.5 THz. Among future ground-based THz facilities we focus on the Greenland Telescope (GLT), whose dish size and angular resolution are 12 m and 4″(at 1.5 THz). The largest advantage of those ground-based telescopes is better angular resolutions, although the sensitivity is worse than *SPICA*. Based on some scientific cases discussed for the GLT, we discuss how *SPICA* can collaborate with ground-based THz telescopes. The shorter-wavelength coverage of *SPICA* than the GLT is suitable for improving dust temperature estimates, and identifying some important chemical species. A high angular resolution of the GLT is crucial to produce high-resolution map or to overcome the confusion limit of *SPICA*. Flexible ToO (Target of Opportunity)-type observations are also worth considering for *SPICA*.

1. INTRODUCTION

The Terahertz (THz) frequency band is a largely unexplored domain in radio astronomy. The Greenland Telescope (GLT; Grimes & Blundell 2012; Inoue 2013) will provide a unique opportunity to explore THz windows around 1–1.5 THz. In addition to its main mission to image the black hole shadow in M87 as part of a submillimeter (submm) interferometer, the GLT is also capable to serve as a powerful single element telescope for a great fraction of time. Currently, the GLT is planned to start observations around 2016.

The merit of ground-based THz observations is that we can use a large telescope. The diameter of the GLT is 12 m, so that the angular resolution achieved is 4″at 1.5 THz, while the diffraction limit of 3.5-m-class space telescopes such as Herschel and *SPICA* is ∼12″at ∼1.5 THz. Therefore, compared with space telescopes such as Herschel and *SPICA*, the GLT is suitable for objects whose interesting structures in THz have an angular scale of a few arcsec.

In the following sections, we first explain unique science cases carried out by the GLT. Based on these cases, we describe possible collaboration between *SPICA* and the GLT. Although we focus on the GLT, the ideas described in this contribution can be applied to any ground-based THz telescopes to be constructed in the future, such as CCAT.[1]

2. THZ SCIENCE CASES FOR THE GLT

A major advantage of moving to higher frequencies into the THz regime is that thermal dust continuum emission will be measured around its peak in the spectral energy distribution (SED). Moreover the GLT angular resolution (4″at 1.5 THz) enable us to spatially resolve the individual star formation sites within nearby molecular clouds ($d < 1$ kpc). These two points would be big advantages especially searching for less massive pre- and proto-stellar populations (e.g., brown dwarf mass or even less massive sources) and constrain the core mass function at the lower mass end. Furthermore, in combination with multi-frequency data, this will allow us to measure SEDs of pre- and proto-stellar sources and determine their cool-gas temperatures ∼10 K, thus providing access to the earliest evolutionary phases of star formation.

Dust continuum observations in the THz regime will also play an important role for nearby galaxies. Dust emission is often used as a tracer for star-formation activities. Here, determining the dust temperature is paramount. Combining lower frequency bands with the 1.5 THz dust emission will significantly improve dust temperature estimates. Moreover, we emphasize that the GLT 1.5 THz achieves an angular resolution comparable to submm interferometric data taken by the Submillimeter Array (SMA) (Figure 1). No THz facilities have ever had such a resolution.

Spectral line studies will complement the THz continuum observations. A wealth of interesting but unexplored lines are in the THz windows (Table 1). High-*J* molecular lines (e.g., CO, HCN) will probe extremely hot (300–500 K) molecular regions in the vicinities (<10 AU) of forming protostars. Line profiles will reveal gas motions in these regions. CONDOR

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

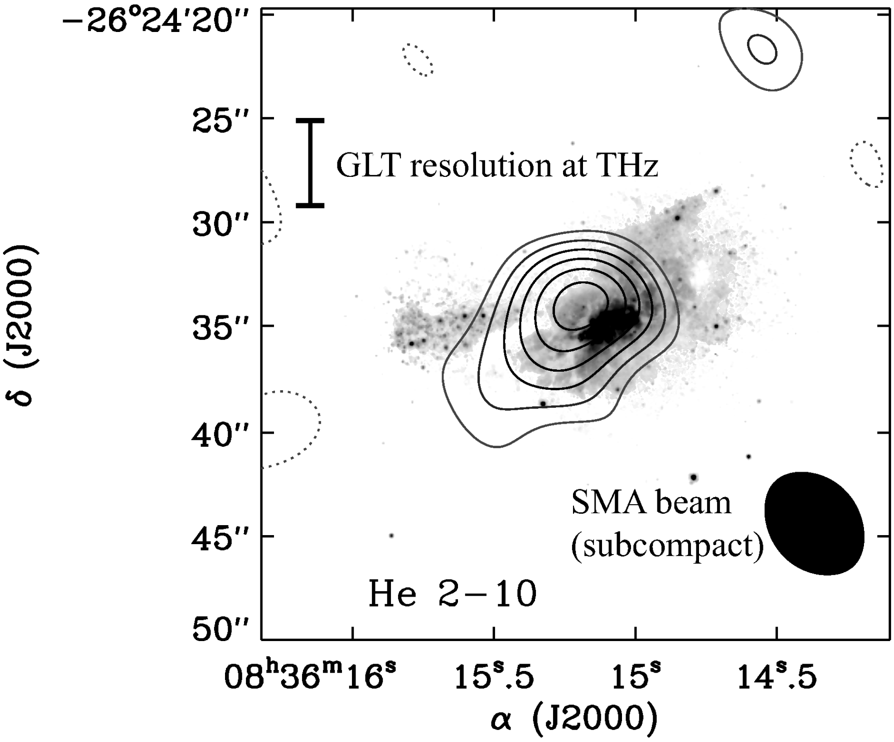

Figure 1. Contour: SMA 880 μm continuum brightness of a nearby dwarf galaxy He 2-10 (see Hirashita 2013, for details). The beam of the subcompact configuration of SMA is shown in the lower right corner. Gray scale: Hubble Space Telescope Advanced Camera for Surveys optical images at *F550M* band. The spatial resolution of the GLT at 1.5 THz (4″) is also shown in the upper left corner.

on APEX already detected the CO (J = 13–12) line at 1.50 THz toward Orion FIR 4, measuring the very hot molecular gas (~200 K) concentrated around the high-mass protostar without contamination from the more extended outflow (Wiedner et al. 2006). Additional lines accessible in the THz windows will be groups of atomic fine-structure lines (e.g., [N II], [C II]), tracing diffuse transitional regions from ionized or atomic gas to molecular gas in the interstellar medium, and pure rotational lines (e.g., CH), tracing chemically basic light molecules.

Table 1. Representative Tera-Hertz Lines

Species	Frequency (THz)	Transition	Excitation energy (K)
CO	1.03691239–1.95601814	(9–8)–(17–16)	248.87486–845.59418
HCO^+	1.06969429–1.33671568	(12–11)–(15–14)	333.77154–513.41458
HCN	1.06298070–1.59334152	(12–11)–(18–17)	331.68253–726.88341
H_2D^+	1.37014600	$1_{0,1}$–$0_{0,0}$	65.75626
N II	1.46113141	$^3P_1$–$^3P_0$	—
CH	1.47073960	N=2, J=3/2-3/2, F=2^+–2^-	96.31131
HD_2^+	1.47660550	$1_{1,1}$–$0_{0,0}$	70.86548
C II	1.90053690	$^2P_{3/2}$–$^2P_{1/2}$	91.21086
O I	2.06006886	$^3P_0$–$^3P_1$	—

In the field of very-high-energy (VHE) phenomena, THz continuum observations can help to constrain the mechanism and region of origin of the VHE in active galactic nuclei (AGNs). In particular, current multi-frequency monitoring campaigns from optical to X- and gamma-rays lack observations in the THz window for a complete SED to constrain the underlying physics of the origin of VHE. THz/submm observations will also help advancing gamma-ray burst (GRB) research. THz continuum observations will provide clean measurements of the source intensity, without being affected by scintillation and extinction. Afterglow properties can be constrained with THz observations because the forward-shock synchrotron peak frequency is falling to lower frequencies with time. Catching the shock in the THz range, and comparing these data with optical and infrared wavelengths will set constraints on the fireball model by constraining the density profile around the GRB. A systematic reverse-shock emission search with the GLT is also imperative to explore the first stars in the early Universe (at redshifts $z\sim10$–30), because the luminosity of reverse-shock emission is expected to be 100 times brighter than that of forward shock emission. For this purpose, a rapid-responding system is necessary for the GLT.

3. POSSIBLE COLLABORATIONS BETWEEN *SPICA* AND THE GLT

The good angular resolution (4″at 1.5 THz) is one of the largest advantages of the GLT, and this is also true for other future ground-based THz telescopes. *SPICA* can achieve the same resolution at 50 μm. Therefore, the spatial resolution of *SPICA* mid-infrared observations matches that of the GLT. The high resolution of the GLT has also an advantage in comparing with interferometric data at longer wavelengths (Figure 1).

Another general feature of ground-based facilities is that they are capable of executing time-consuming observations. In contrast, space observatories are not suitable for time-consuming projects because of their limited lifetimes. Therefore, if we have found interesting objects by the GLT, they are viable targets of *SPICA*.

Below, we describe possible collaboration items between *SPICA* and the GLT for some of the specific science cases reviewed in Section 2. We choose (i) warm environments, (ii) dust formation and evolution, and (iii) time-variable sources as viable topics for such a collaboration.

3.1. Warm Environments

One of the unique points in THz observations is capability of observing highly excited CO, which is a tracer of dense and warm gas (hydrogen number density $\gtrsim 10^5$ cm^{-3} and temperature 300–500 K). Such a highly excited tracer is suitable to probe the vicinity of protostars and AGNs. On the other hand, mid-infrared spectroscopy is one of the strongest tools for investigating various chemical species in various environments. For example, an AGN with high excitation CO lines (NGC 1068; Hailey-Dunsheath et al. 2012) emits strong HCN lines (Krips et al. 2011), but so far there is no definite explanation for it. *SPICA* can target this kind of AGNs to observe vibration-rotation absorption bands of some molecular species (such as HCN 14 μm Lahuis et al. 2007), further constraining the emission mechanism.

The [N II] 1.46 THz (205 μm) can also be observed by the GLT. By *SPICA*, we can additionally observe [O I] 63 μm and [C II] 158 μm. These atomic lines trace diffuse (30–100 cm^{-3}), transitional regions from ionized or atomic gas to molecular gas in the ISM, so that they are unique tracers of H II regions, photo-dissociation regions, and the surface of molecular clouds. In particular, obtaining the radiation field intensity (Pineda et al. 2010) and density (Oberst et al. 2011), and extracting kinematic information from the line profiles are crucial steps to reveal the cloud formation and disruption processes.

3.2. Dust Formation and Evolution

Precise measurement of dust mass is a crucial step in clarifying the dust enrichment in the Universe. There are two major uncertainties in measuring dust mass: one is the dust temperature and the other is the dust mass absorption coefficient.

The dust temperature is most precisely determined if we observe at wavelengths near the dust SED peak, which is located around 100 μm depending on the dust temperature. Although the THz windows accessible for the GLT contribute to improving dust temperature estimates significantly, adding a shorter wavelength such as 100 μm is desirable for further precision. Therefore, follow-up observations of GLT sources by *SPICA* around 100 μm contribute to improving dust mass estimates. By combining the better estimate of dust temperature by *SPICA* and the better spatial resolution of the GLT, we can make a high-resolution dust temperature map.

The uncertainty in the mass absorption coefficient may be overcome by knowing the dust species from mid-infrared spectroscopic observations by *SPICA*. Indeed, Markwick-Kemper et al. (2007) determine the mineralogical composition of dust in an AGN environment (a broad absorption line quasar PG 2112+059) by fitting the dust spectral features. Since such an identification of dust species is difficult for THz featureless continuum, *SPICA* mid-infrared observations will provide unique information on dust species.

In Figure 2, we show another example of spectral fitting: the observed SED of a planetary nebula NGC 6781 overlaid with the best-fit CLOUDY (Ferland et al. 2013) model (Otsuka et al., in preparation). In particular, the wavelength range covered by *SPICA* and the GLT is important for the dust emission. Thus, combination of *SPICA* and the GLT will contribute to precise determination of the dust mass contained in mass-loss objects such as planetary nebulae, asymptotic giant branch stars, etc., to better understand the total dust supply rate by those sources in the Galaxy. THz (and submm) measurements by the GLT is of fundamental importance in determining the cold dust mass, which has the largest contribution to the total dust mass.

For high-redshift galaxy surveys, it is worth noting that *SPICA* still has a problem of confusion limit for far-infrared continuum observations. Therefore, a high-resolution follow-up observations by the GLT is crucial to isolate spatially contaminated sources.

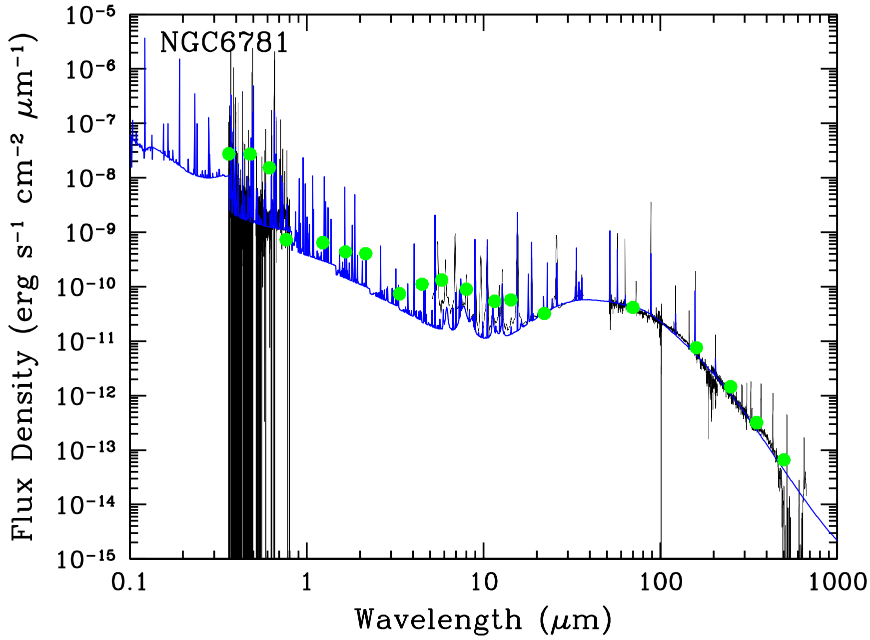

Figure 2. The best-fit SED calculated by CLOUDY overlaid on the photometric (dots: INT/WFC, 2MASS, *Spitzer* IRAC, *AKARI* PSC, *Herschel* PACS and SPIRE) and spectroscopic data (WHT/ISIS, Spitzer IRS, *Herschel* PACS and SPIRE) for a planetary nebula NGC 6781 (Otsuka et al., in preparation).

3.3. **Time-Variable Sources**

Blasars are unique objects to understand AGN activities, such as jets. Measurements of synchrotron-self-absorption SED are especially important to determine the magnetic field strengths associated with the energetic phenomena. However, the far-infrared–submm region is the unexplored part in the SED (Abdo et al. 2011). Therefore, a possibility of simultaneous observations between *SPICA* and a ground-based submm telescope is interesting in filling the SED gap in the far-infrared–submm region. For this purpose, it is worth considering a flexible operation mode for *SPICA* such as a ToO (target of opportunity) mode. Campaign observations of GRBs and SNe between *SPICA* and the GLT are also interesting if there is such a flexible operation mode.

4. **SUMMARY**

We will be able to carry out fruitful collaborations between *SPICA* and the GLT by utilizing the following complementary characteristics: *SPICA* has a coverage of wavelengths shorter than 200 μm while the GLT has a higher resolution at $>$200 μm. Specifically, the GLT can overcome the confusion limit of *SPICA* at far-infrared wavelengths, while *SPICA* can follow up GLT objects at $\sim$100 μm, obtaining better estimates of dust temperature and dust mass. Moreover, *SPICA* can clarify dust species and physical states of the ISM by mid-infrared spectroscopic observations, which are capable of detecting plenty of lines and features. Flexible ToO-type operations are also worth considering for *SPICA*.

HH acknowledges the support of NSC grant NSC102-2119-M-001-006-MY3.

REFERENCES

Abdo, A. A., et al. 2011, ApJ, 726, 43
Ferland, G. J., et al. 2013, Rev. Mexicana Astron. Astrofis., 49, 1
Grimes, P., & Blundell, R. 2012, Proc. SPIE, 8444, 84441N
Hailey-Dunsheath, S., et al. 2012, ApJ, 755, 57

Krips, M., et al. 2011, ApJ, 736, 37
Lahuis, F., et al. 2007, ApJ, 659, 296
Markwick-Kemper, F., Gallagher, S. C., Hines, D. C., & Bouwman, J. 2007, ApJ, 668, L107
Hirashita, H. 2013, MNRAS, 429, 3390
Inoue, M. 2013, in Astrophysics from Antarctica, IAU Symp. 288, ed. M. G. Burton, X. Cui, & N. F. H. Tothill (Cambridge: Cambridge University Press), 200
Oberst, T. E., Parshley, S. C., Nikola, T., et al. 2011, ApJ, 739, 25
Pineda, J. L., Velusamy, T., Langer, W. D., et al. 2010, A&A, 521, 19
Wiedner, M. C., et al. 2006, A&A, 454, L33 MNRAS, 432, 637