Exploration of cosmic star formation history using LST

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Unveiling the dust-obscured part of the cosmic star-formation history is one of the biggest challenges in the modern astrophysics. Intensive surveys using airborne and ground-based facilities at (sub)millimeter to far-infrared wavelengths have revealed that the majority of the cosmic star formation at $z = 1 - 3$, where the cosmic star-formation rate density (SFRD) peaks, seems to be obscured by dust (e.g., Burgarella et al. 2013). However, SFRDs beyond redshift > 3 – 4 have been mostly investigated by the rest-frame ultra-violet emission (e.g., Bouwens et al., 2015, Ono et al., 2018), and the roles of the dust-obscured star-formation largely remain unsettled (e.g., Bouwens et al., 2016, Rowan-Robinson et al. 2016). Now a large amount of the ALMA observing time has been invested to conduct deep continuum surveys (e.g., Dunlop et al. 2017) as well as spectral scans to uncover line emitting galaxies traced by CO and [CII] lines (e.g., Aravena et al. 2016, Gonzalez-Lopez et al. 2017). Furthermore, a large number of targeted observations in continuum (e.g., Scoville et al. 2016) have yielded improved estimation of cosmic SFRD history up to $z \sim 6$, and recently targeted spectroscopy of lensed Lyman break galaxies uncovers the earliest metals known to date up to $z \sim 9$ by exploiting the bright [OIII] 88 μm nebular line (e.g., Hashimoto et al. 2018). Nevertheless, the survey volume of these ALMA observations is still limited due to the narrowness of the instantaneous ALMA field of view (FoV).

By exploiting the state-of-the-art direct detector technologies, the LST, with a large FoV (0.5 degree diameter or larger), will facilitate groundbreaking exploration of an extremely large 3D volume of the universe and, also, completely new advancements in time-domain science for millimeter and submillimeter astronomy. The LST is very complementary to ALMA and can establish an unbiased census of metal-enriched high-redshift galaxies through wide-field spectroscopic and continuum surveys. The LST can also identify intriguing sources for further investigation by ALMA. By exploiting the synergy with ALMA and other survey-oriented existing and near-future missions in the optical to far-infrared ranges, including HSC/PFS on Subaru, TAO, LSST, Euclid, WFIRST, and SPICA, the LST can contribute to a broad range of research in astronomy and astrophysics. Here we focus on 3 key science cases to unveil the dust-obscured part of the cosmic SFRD history up to an early phase of galaxy formation, i.e., during the epoch of reionization (EoR).

1. Blind spectroscopic survey of CO, [CII], and [OIII] line emitting galaxies

(CO/[CII]/[OIII] tomography)

A novel approach to elucidation of cosmic star formation history is a blind spectroscopy search for CO and [C II] emitting galaxies. In particular, searching for [C II] emitters in the appropriate frequency range allows us to sample those sources very efficiently for a redshift range of 3.5 to 9 (190 to 420 GHz), reaching the star-formation in the EoR. Further, spectroscopic analysis of CO in the lower frequency bands offers an opportunity to constrain the evolution of CO luminosity functions across cosmic time. This approach is referred to as ``CO/[C II] tomography'', because it is a CO/[C II] analog to the HI 21-cm tomography that will be conducted with the Square Kilometer Array (SKA). Such a spectroscopic deep survey will not be severely affected by source confusion noise, unlike continuum surveys, and can potentially detect fainter high-z galaxies. Recent successful blind or serendipitous detections of CO- and [C II]-line emitting galaxies using ALMA (e.g., Tamura et al. 2014; Walter et al. 2016) also advance our plan.

A feasibility study of CO/[C II] tomography has been conducted based on a mock galaxy catalog containing 1.4 million objects with CO flux S(CO) δv ≥ 0.01 Jy km/s, drawn from the S^3−SAX project (Obreschkow et al. 2009). The model predicts CO fluxes of mock galaxies, and the [CII] fluxes, which are not available in the model, are computed by assuming a [CII] to CO(1-0) luminosity ratio of 4,100 (Stacy et al. 2010). Here we assumed a 100 pixel, dual-polarization receiver array with an instantaneous frequency coverage of 70 to 370 GHz. This can be very challenging specifications if we compare them with the existing heterodyne-based receivers, but we expect that it can be implemented by exploiting the DESHIMA technology, an on-chip super-conducting spectrograph with a moderate spectral resolution (Endo et al. 2012). By spending 1,000 hours (on-source) toward an area of 2 deg^2, we find that the survey can detect more ~22,000 CO-emitting galaxies, and ~1,200 [CII] emitters above $z > 4$. The derived 2 deg^2 light cone, source densities of CO and [CII] line emitters, and the number counts of CO and [CII] line emitters, are shown in Figure 1. With these line emitters, we will drastically improve the constraints on the CO and [CII] luminosity functions, especially for the bright ends of the luminosity functions, which will give an indispensable clue for the formation of massive galaxies. Note that the presented feasibility study does not include [OIII] 88 μm line, which becomes a very powerful probe to study galaxies during the EoR (e.g., Inoue et al. 2016, Hashimoto et al. 2018; Tamura et al. 2018), so the number of galaxies during the EoR will be increased significantly. A quantitative estimation of the number density of such [OIII] emitting galaxies is in progress based on numerical simulations.

Such spectroscopic surveys can also be useful for the characterization of dark halo masses hosting these star-forming populations, which are traced by CO and [CII] lines, and study of the growth rate of cosmic large-scale structures by measuring redshift space distortion (RSD) for CO-emitting galaxies at a redshift range beyond 2. These data will constitute complementary RSD measurements to those obtained via optical/near-infrared redshift surveys (e.g., Okumura et al. 2016, Zarrouk et al. 2018 and references therein). By conducting a 5,000 hours (on-source) unbiased spectroscopic survey toward 100 deg^2 area, using a 1,000-pixel array receiver, we will be able to have ~10^6 CO emitters and 5 x 10^4 [CII] emitters. Such a data set allows us to put constraints on the linear growth rate f = dln(D)/dln(a), and the estimated fractional error of $f(z)\sigma_8(z)$ for a redshift bin of dz = 0.5 will be 5% at z = 2.0 and 8% at z = 3.0. Although Lyα-based RSD measurements like HETDEX will produce better constraints on the $f(z)\sigma_8(z)$ up to z~3, multi-tracer measurements by combining LST measurements may help to defeat cosmic variance (e.g., Seljak 2009). Such spectroscopic surveys will also allow us to conduct the intensity mapping, and further feasibility test on the intensity mapping technique is in progress.

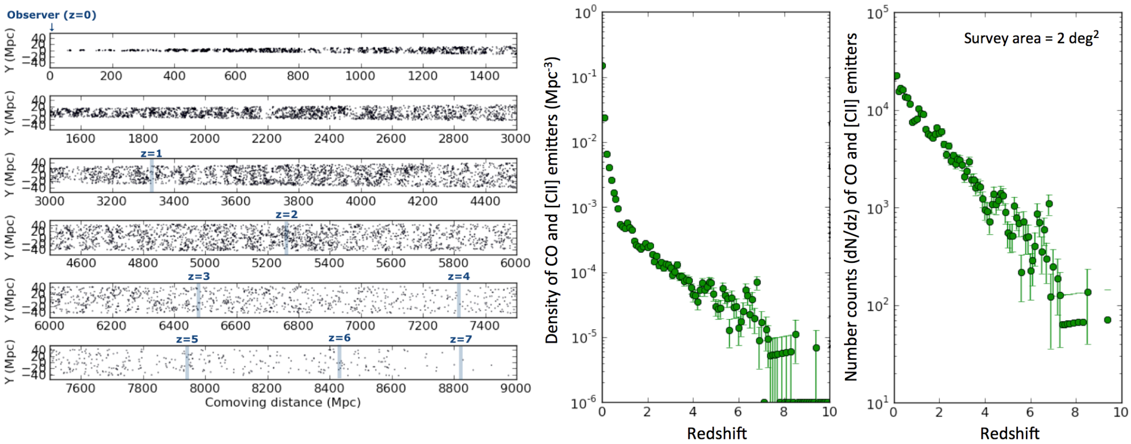

Figure 1: A feasibility study of CO/[CII] tomography using LST equipped with a 100-pixel ultra-wide-band imaging spectrograph (Tamura et al., in prep.). (Left) A simulated light cone of the proposed 2 deg^2 spectroscopic deep survey spending 1,000 hours (on-source). (Middle) The expected volume density of CO and [CII] emitting galaxies as a function of redshift. (Right) Number counts of CO and [CII] emitters.

2. A search for Pop-III long Gamma-ray bursts by a high-cadence continuum imaging survey

Another unique approach to uncover star-forming galaxies during the EoR is to detect the Synchrotron emission from the reverse shock of the long-duration GRBs (hereafter simply GRBs). Inoue et al. (2007) showed that the reverse shock component of the Pop-III GRBs at z = 15 to 30 in the 300 GHz band can be substantially brighter than 1 mJy. In order to catch the reverse shock emission from a GRB, immediate follow-up observations at a time scale of a few hours to ~10 hours (i.e., less than 1 day) are necessary. Due to the difficulty of such time-critical observations of GRBs, the study of the reverse shock emission remains largely unexplored yet. Nevertheless, a recent successful detection of the reverse shock component from GRB 120326A at z = 1.798, which was detected by 1.3 mm observations using SMA at ~17 hours after the burst, has demonstrated that such prompt mm-wave continuum measurements can catch the brightest part of the SED from a GRB at a cosmological distance (Urata et al. 2014). Immediate follow-up observations of the reported GRBs using a single dish telescope such as Green Land Telescope (GLT; Urata et al. 2015) and LST can be very useful to study the nature of such reverse shock component of high-z GRBs (note that currently ALMA is not sufficiently flexible to conduct such a few hour scale immediate follow-ups of time-critical sources).

Eventually, the ultra-fast mapping capability of LST may allow us a blind search for mm-wave flashes by conducting an ultra-wide-area (>100 deg^2) high-cadence (less than 10 hours per one map) continuum imaging survey, once we achieve a superb mapping speed such as a few 10 deg^2 mJy^{-2} hr^{-1}. Although the number density of such GRBs with bright reverse shock emission during the EoR is not yet constrained, the proposed high cadence imaging survey at ~1 mm using LST will provide a new and unique pathway for the study of Pop-III stars up to z~30.

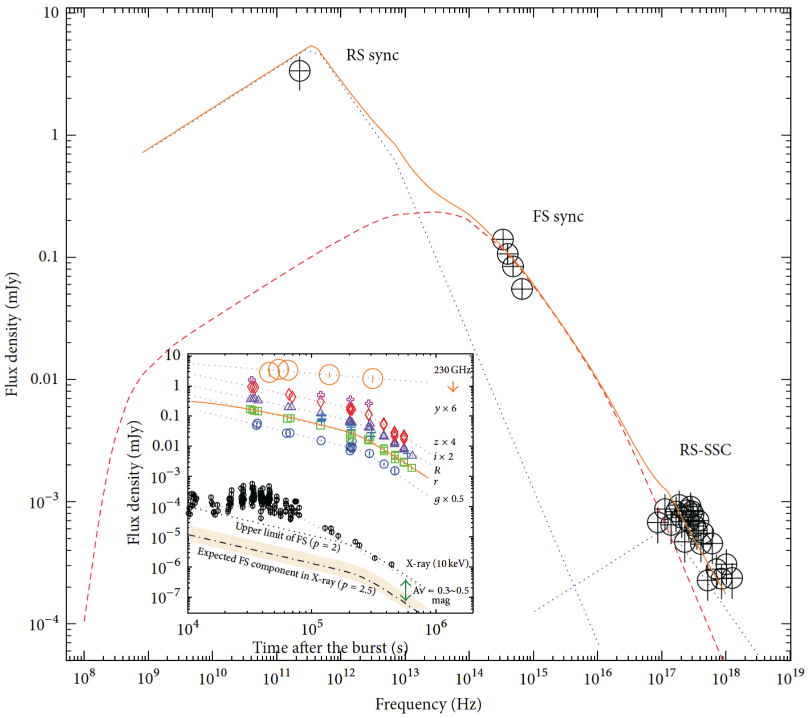

Figure 2: The spectral energy distribution of GRB120326A at ~17 hours after the burst (Urata et al. 2014). Taken from Urata et al. (2015).

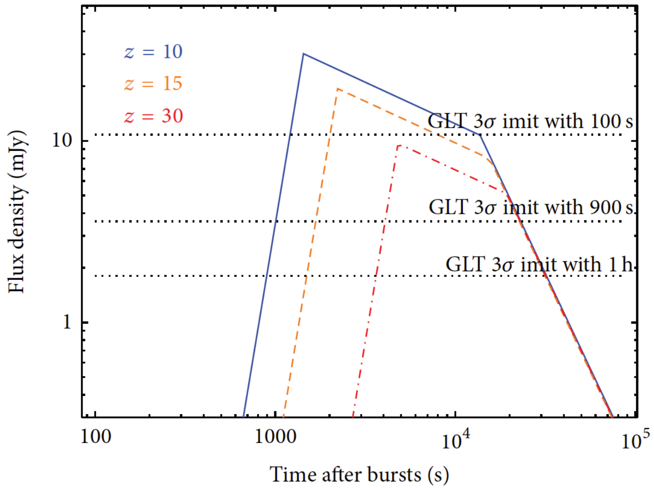

Figure 3: Expected light curves of GRB afterglows at z = 10, 15, and 30 at 230 GHz (1.3 mm). Taken from Urata et al. (2015). The expected 3 sigma limits using the Green Land Telescope are shown. The LST can conduct a blind multi-epoch surveys, which may allow us to blindly uncover the reverse shock emission from distant GRBs as a mm-wave flash.

3. Uncovering dusty star-forming galaxies during the EoR by confusion-limited deep 1.3mm to 850μm surveys

Millimeter and submillimeter wavelengths are best suited for detecting re-processed thermal dust emission in the early Universe via the strong negative K-correction. Wide-field multi-band continuum imaging surveys with a high angular resolution (a few arcsec) will allow us to uncover the large-scale structures of dusty star-forming galaxies. A resolution of a few arcsec, which is achieved with the proposed 50-m class single dish telescope, is essential to beat the source confusion limit of the existing single dish telescopes (except for the LMT 50-m telescope). Recent ALMA detections of dust emission from lensed Lyman break galaxies such as Abell 1689-zD1 at z = 7.5±0.2 (0.56±0.1 mJy at 1.3mm, and 1.33±0.14 mJy at 870μm, Watson et al. 2015; Knudsen et al. 2017) and MACS J0416.1_Y1 at z = 8.3118±0.0003 (0.137±0.026 mJy at 850 μm, Tamura et al. 2018) have demonstrated that dusty galaxies during the EoR can be bright at 1.3 mm to 850 μm wavelengths. These levels of the continuum emission are well above the 5 sigma confusion limit of the LST, i.e., 0.12 mJy (Table 1). The superb continuum mapping speeds at 1.3mm to 850 μm bands will, therefore, allow us to search for dusty galaxies up to z ~ 10 if such galaxies exist.

A sharp beam size (~5 arcsec) achieved using LST is also useful for efficient and reliable multi-wavelength counterpart identification and the resultant determination of the photometric redshifts of these dusty galaxies without interferometric follow-up. Recent high-resolution ALMA studies of submillimeter galaxies uncovered by ground-based 10-15 m class telescopes and Herschel/SPIRE (all with >10-arcsec resolutions) reveal that these galaxies are often composed of multiple sources due to a large observing beam (e.g., Simpson et al. 2015).

Table 1a: Confusion limits (mJy, 5σ) as functions of the observing wavelengths and telescope diameters. Based on the modeled number counts given by Bethermin et al. (2012). The adopted definition of the source confusion is 12 beams per source.

	LMT, LST	IRAM	(CCAT)	JCMT	APEX	ASTE etc.
Diameter	50m	30m	25m	15m	12m	10m
3.3 mm	0.031	0.055	0.065	0.10	0.12	0.14
2.0 mm	0.068	0.14	0.17	0.29	0.36	0.42
1.3 mm	0.12	0.32	0.41	0.76	0.96	1.1
1.1 mm	0.14	0.40	0.53	1.0	1.3	1.6
850 μm	0.12	0.47	0.66	1.4	1.8	2.2
750 μm	0.11	0.60	0.87	1.9	2.5	3.1
450 μm	0.005	0.34	0.71	2.4	3.5	4.5
350 μm	0.0003	0.092	0.33	2.0	3.2	4.3

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