Galaxies at High Redshift and Their Evolution Over Cosmic Time
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SXDF-UDS-CANDELS-ALMA 1.5 arcmin^2 deep survey

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Abstract. We have conducted 1.1 mm ALMA observations of a contiguous $105'' \times 50''$ or 1.5 arcmin^2 window in the SXDF-UDS-CANDELS. We achieved a 5σ sensitivity of 0.28 mJy, giving a flat sensus of dusty star-forming galaxies with $L_{\rm IR} \sim 6 \times 10^{11}$ $L_\odot$ (if $T_{\rm dust}$ =40K) up to $z \sim 10$ thanks to the negative K-correction at this wavelength. We detected 5 brightest sources (S/N>6) and 18 low-significant sources (5>S/N>4; they may contain spurious detections, though). One of the 5 brightest ALMA sources ($S_{\rm 1.1mm} = 0.84 \pm 0.09$ mJy) is extremely faint in the WFC3 and VLT/HAWK-I images, demonstrating that a contiguous ALMA imaging survey uncovers a faint dust-obscured population invisible in the deep optical/near-infrared surveys. We find a possible [CII]-line emitter at $z = 5.955$ or a low-z CO emitting galaxy within the field, allowing us to constrain the [CII] and/or CO luminosity functions across the history of the universe.

Keywords. galaxies: starburst – galaxies: high-redshift – submillimeter

1. Introduction

Deep mm/submm surveys using single dish telescopes with detector arrays have revolutionized observational cosmology by uncovering a new population of submillimeter galaxies (SMGs); dusty, extreme star-forming populations in the early universe (e.g., Casey *et al.* 2014). Recent extensive follow up studies of SMGs using ALMA have brought new insights on the nature of these extreme sources, such as their redshift distributions, multiplicity (revising the number counts), and source sizes (e.g., Karim *et al.* 2013 for APEX/LABOCA sources in ECDF-S, Simpson *et al.* 2015 for JCMT/SCUBA2 sources in UDS, and Ikarashi *et al.* 2015 for ASTE/AzTEC sources in SXDF). However, despite their enormous IR luminosities ($L_{\rm IR} \sim 10^{13} L_\odot$), the contribution of SMGs to the extragalactic background light (EBL), which represents the integrated unresolved emission from extragalactic sources and contains vital information on the history of galaxy formation, is rather minor (e.g., ∼10 – 20 % at 1.1 mm; Scott *et al.* 2012). In fact, recent ALMA observations suggest that *faint SMGs* or *sub-mJy sources*, i.e., mm-selected sources with $S_{\rm 1mm} < 1$ mJy, may account for $\sim 50 - 100\%$ of the EBL at 1.1 to 1.3 mm bands (e.g., Hatsukade *et al.* 2013; Ono *et al.* 2014; Carniani *et al.* 2015; Fujimoto *et al.* 2015), although little is known about the physical properties, such as their redshift distribution and stellar masses, of these newly discovered sources, partly because sub-mJy galaxies are often faint in NIR/radio at the current sensitivities.

Here we present an overview of ALMA 1.1 mm (Band 6) imaging survey of sub-mJy galaxies in a contiguous $105'' \times 50''$ or 1.5 arcmin^2 rectangular window, where deep multiwavelength data sets are available from SXDF, UDS, CANDELS, HUGS, SpUDS, SEDS, and so on (see Galametz *et al.* 2013 for a summary of ancillary data).

2. ALMA observations: strategy and data analysis

The observed region was selected because of the richness of Hα emitting galaxies at $z = 2.53 \pm 0.02$ uncovered by extensive narrow-band filter imaging surveys using MOIRCS camera on Subaru telescope (Tadaki *et al.* 2013) and covered by 19-point mosaic in order to minimize the number of pointing at a cost of the sensitivity uniformity within the mosaic map. This strategy minimizes the fraction of the overhead within the total observing time, given the fact that the overhead for mosaic observations was expected to be rather painful when the cycle 1 call for proposal was issued.

The observations were carried out on 17 and 18 July 2014 under excellent atmospheric conditions with a precipitable water vapor of 0.42 - 0.55 mm. Total observing time was 3.6 hours. During the runs 30 - 32 antennas were available and the range of baseline lengths was from 20 m to 650 m, giving an excellent *uv* coverage despite of the source declination (close to the equator).

The continuum map was processed with the `CLEAN` with the natural weighting using `CASA` package, which gives a synthesized beamsize of $0''.53 \times 0''.41$. A typical noise level is 0.055 mJy beam^{-1} (1σ) near the center of each pointing. The obtained ALMA image is shown in Figure 1. We also created a 3D cube with a frequency width of 60 MHz to search for any mm-wave line emitters using a clump-find algorithm.

3. Results and Discussion: physical properties of ALMA sources

ALMA 1.1 mm continuum sources and their physical properties: We extract significant sources above 4σ using the `AIPS` task `SAD`. We detected 23 sources in total, including 5 brightest sources (S/N>6) and 18 less-significant sources (5>S/N>4). A part of the extracted sources (with S/N larger than 4.3) are listed in Table 1. We estimated false detection rates by counting negative peaks in the map, indicating that sources below 5σ may contain spurious, although the derived number counts are consistent with existing studies after careful estimations of completeness and false detection rate (Hatsukade *et al.* in prep.) utilizing a source finding code `AEGEAN` (Hancock *et al.* 2012).

Multiwavelength properties of 5 brightest ALMA sources have been studied by exploiting the rich data in this field (Yamaguchi *et al.* in prep.), revealing that 4 of ALMA sources are on the main sequence of star-forming galaxies with a significant stellar mass ($M_{\rm star} \sim (4-10) \times 10^{10} M_\odot$) at their epochs ($z_{\rm photo} \sim 1.3 - 2.5$).

New populations of galaxies unveiled by the ALMA 1.1 mm survey: Then does ALMA only detect dust emission from "already known galaxies" selected by rest-frame UV/optical

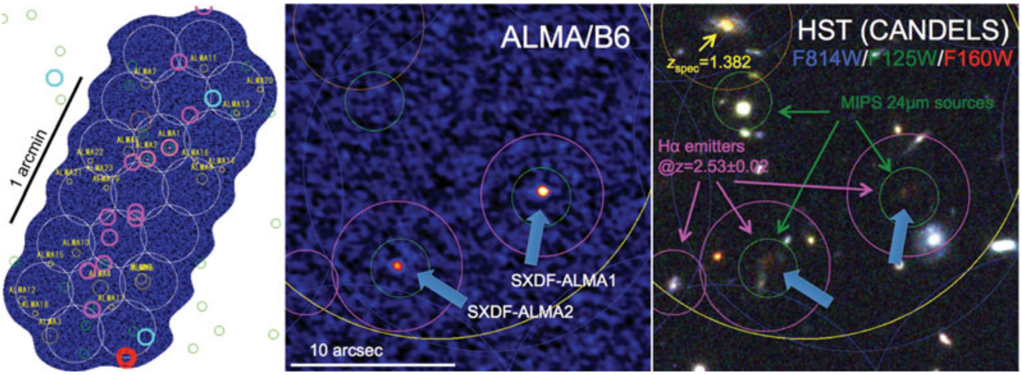

Figure 1. (left) ALMA 1.1mm continuum image obtained by 19 point mosaic (indicated by white circles). Detected 23 ALMA sources are indicated by small yellow circles (larger circles mean higher S/N) with their source ID, and the distribution of Hα emitters at z = 2.53 are shown by small magenta circles. Small green circles are MIPS 24μm sources. (middle) a close up view of ALMA 1.1 mm continuum image showing two brightest sources (SXDF-ALMA1 and 2 in Table 1). (right) a 3-color composite NIR image of the same region. There are 3 Hα emitters, 3 MIPS sources (two of them are overlapped), and 1 star-forming galaxy at $z_{\rm spec}$ = 1.382, and we see a variety of 1.1 mm properties among these galaxies.

Table 1. A catalogue of ALMA 1.1 mm continuum sources in the 1.5 arcmin^2 field

ID	α	δ	$S_{\rm peak}$	S/N	weight[1]	note[2]
SXDF-ALMA1	02 17 40.524	-05 13 10.64	1.696 ± 0.058	29.36	0.952	Hα emitter $z = 2.53 \pm 0.02$
SXDF-ALMA2	02 17 41.120	-05 13 15.19	0.791 ± 0.065	14.27	0.852	Hα emitter $z = 2.53 \pm 0.02$
SXDF-ALMA3	02 17 43.642	-05 14 23.81	0.839 ± 0.090	9.29	0.609	Herschel/JVLA dropout
SXDF-ALMA4	02 17 42.335	-05 14 05.09	0.395 ± 0.056	7.05	0.982	$z_{\rm photo} = 1.33^{+0.10}_{-0.16}$
SXDF-ALMA5	02 17 41.229	-05 14 02.74	0.378 ± 0.056	6.70	0.976	$z_{\rm photo} = 1.52^{+0.13}_{-0.18}$
SXDF-ALMA6	02 17 41.597	-05 13 12.29	0.315 ± 0.067	4.73	0.827	
SXDF-ALMA7	02 17 41.153	-05 12 45.47	0.299 ± 0.065	4.58	0.844	
SXDF-ALMA8	02 17 39.678	-05 13 22.81	0.282 ± 0.062	4.54	0.884	
SXDF-ALMA9	02 17 41.270	-05 14 01.62	0.259 ± 0.057	4.52	0.960	
SXDF-ALMA10	02 17 42.965	-05 13 51.46	0.270 ± 0.061	4.44	0.905	
SXDF-ALMA11	02 17 39.633	-05 12 39.79	0.278 ± 0.063	4.384	0.867	
SXDF-ALMA12	02 17 44.371	-05 14 09.82	0.397 ± 0.091	4.378	0.606	

[1] primary beam correction factor. $S_{\rm peak}$ in this table has been corrected accordingly (1/weight).
[2] source properties from Yamaguchi *et al.* (in prep.)

deep surveys? The answer is no; one of the 5 brightest ALMA detections, SXDF-ALMA3, is extremely faint even in the ultra-deep NIR images from CANDELS and HUGS as shown in Figure 2. Further contributions to the star formation history may come from these faint submm galaxies which do not appear to be fully overlapped with UV/optical-selected galaxies (e.g., Chen *et al.* 2014).

Another new type of ALMA sources is a mm-wave line emitting galaxy; we find a promising candidate of a line emitting galaxy at an observing frequency of ~273.3 GHz with a peak flux of 3.8 ± 0.70 mJy (5.4σ) or a velocity-integrated line flux of 0.53 ± 0.079 Jy km s^{-1} (6.7σ) exhibiting a galaxy-like line width (FWHM ~100 km s^{-1}). Although it is not yet clear if this is a [CII] emitter at z = 5.955 or a low-z CO emitting galaxy at this stage, this result encourages us to search for such mm-wave line emitters using ALMA data, allowing us to constrain [CII] and/or CO luminosity functions across the history of the universe (e.g., Ono *et al.* 2014, Tamura *et al.* 2014, Matsuda *et al.* 2015).

Implications for future ALMA deep surveys: We find a rapid increase of the number of faint ALMA sources below ~0.3 mJy as expected by latest source counts around 1 mm,

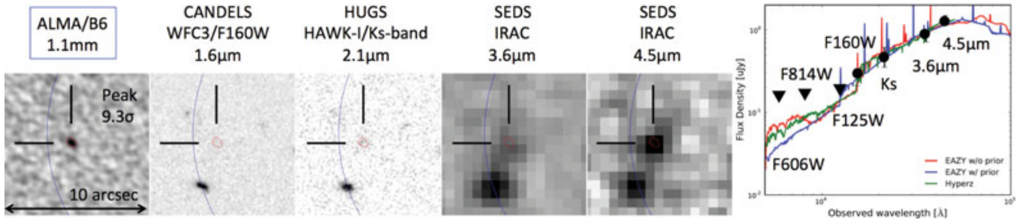

Figure 2. Multi-wavelength view of SXDF-ALMA3 together with the best-fit SED (Yamaguchi *et al.*, in prep.). Despite the fact that SXDF-ALMA3 has an elevated star-formation ($S_{1.1\mathrm{mm}} = 0.84 \pm 0.09$ mJy or SFR $\sim$200 $M_\odot$ yr^{-1} if $T_{\mathrm{dust}} = 35$ K), it is very dark even in deep WFC3/F160W (CANDELS-wide; 5σ limiting magnitude = 27.45 m_{AB}) and HAWK-I/$\mathrm{K_S}$-band (HUGS; 5σ limiting magnitude =26.16 m_{AB}) images. This is a SPIRE drop source.

demonstrating that undertaking a shallower survey by a factor of $\sim$2 would drastically reduce the detections (only 3 sources above 4σ!). Our recent deep ALMA band 6 survey of the central 4.5 arcmin^2 region of SSA22 field (which shows an extreme overdensity at $z = 3.1$, Tamura *et al.* 2009) with a similar depth (1σ 0.07 mJy at 1.1 mm; Umehata *et al.* 2015) also supports this view. It is also noteworthy to mention the rapid progress of new large single dishes such as LMT 32 m (to be extended to 50 m) with AzTEC. Recently it demonstrates a survey depth down to 0.17 mJy (1σ) at 1.1 mm to constrain the rest-FIR properties of a $z_{\mathrm{photo}} = 9.6$ galaxy (Zavala *et al.* 2015), suggesting that much deeper depths will ensure the unique parameter space exploiting the unique ALMA capabilities.

This makes use of the following ALMA data: ADS/JAO.ALMA#2012.1.00756.S.

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