

ALMA twenty-six arcmin² survey of GOODS-S at one millimeter (ASGAO): Source catalog and number counts

Bunyo HATSUKADE,^{1,*} Kotaro KOHNO ,^{1,2} Yuki YAMAGUCHI,¹
Hideki UMEHATA,^{1,3} Yiping AO,⁴ Itziar ARETXAGA,⁵ Karina I. CAPUTI,⁶
James S. DUNLOP,⁷ Eiichi EGAMI,⁸ Daniel ESPADA,^{9,10} Seiji FUJIMOTO,¹¹
Natsuki H. HAYATSU,^{12,13} David H. HUGHES,⁵ Soh IKARASHI,⁶ Daisuke IONO,^{9,10}
Rob J. IVISON,^{13,7} Ryohei KAWABE,^{9,10,14} Tadayuki KODAMA,¹⁵ Minju LEE,¹⁶
Yuichi MATSUDA,^{9,10} Kouichiro NAKANISHI,^{9,10} Kouji OHTA,¹⁷
Masami OUCHI,^{11,18} Wiphu RUJOPAKARN,^{18,19,20} Tomoko SUZUKI,⁹
Yoichi TAMURA,¹⁶ Yoshihiro UEDA,¹⁷ Tao WANG,^{1,9} Wei-Hao WANG,²¹
Grant W. WILSON,²² Yuki YOSHIMURA,¹ and Min S. YUN²²

¹Institute of Astronomy, Graduate School of Science, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan

²Research Center for the Early Universe, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

³RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

⁴Purple Mountain Observatory & Key Laboratory for Radio Astronomy, Chinese Academy of Sciences, 8 Yuanhua Road, Nanjing 210034, China

⁵Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Luis Enrique Erro 1, Sta. Ma. Tonantzintla, Puebla, Mexico

⁶Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700AV Groningen, The Netherlands

⁷Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

⁸Steward Observatory, University of Arizona, 933 N. Cherry Ave, Tucson, AZ 85721, USA

⁹National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

¹⁰SOKENDAI (The Graduate University for Advanced Studies), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

¹¹Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa, Chiba 277-8582, Japan

¹²Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

¹³European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

¹⁴Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

¹⁵Astronomical Institute, Tohoku University, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan

¹⁶Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan

¹⁷Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan

¹⁸Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, The University of Tokyo (Kavli IPMU, WPI), 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan

¹⁹Department of Physics, Faculty of Science, Chulalongkorn University, 254 Phayathai Road, Pathumwan, Bangkok 10330, Thailand

²⁰National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, Mae Rim, Chiang Mai 50180, Thailand

²¹Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 10617, Taiwan

²²Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA

*E-mail: hatsukade@ioa.s.u-tokyo.ac.jp

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Abstract

We present the survey design, data reduction, construction of images, and source catalog of the Atacama Large Millimeter/submillimeter Array (ALMA) twenty-six arcmin² survey of GOODS-S at one millimeter (ASAGAO). ASAGAO is a deep (1σ depth $\sim 61\ \mu\text{Jy beam}^{-1}$ for a $250\ \text{k}\lambda$ -tapered map with a synthesized beam size of $0''.51 \times 0''.45$) and wide area ($26\ \text{arcmin}^2$) survey on a contiguous field at 1.2 mm. By combining with ALMA archival data in the GOODS-South field, we obtained a deeper map in the same region (1σ depth $\sim 30\ \mu\text{Jy beam}^{-1}$ for a deep region with a $250\ \text{k}\lambda$ -taper, and a synthesized beam size of $0''.59 \times 0''.53$), providing the largest sample of sources (25 sources at $\geq 5.0\sigma$, 45 sources at $\geq 4.5\sigma$) among ALMA blank-field surveys to date. The number counts show that $52_{-8}^{+11}\%$ of the extragalactic background light at 1.2 mm is resolved into discrete sources at $S_{1.2\ \text{mm}} > 135\ \mu\text{Jy}$. We create infrared (IR) luminosity functions (LFs) in the redshift range of $z = 1\text{--}3$ from the ASAGAO sources with K_s -band counterparts, and constrain the faintest luminosity of the LF at $2.0 < z < 3.0$. The LFs are consistent with previous results based on other ALMA and SCUBA-2 observations, which suggest a positive luminosity evolution and negative density evolution with increasing redshift. We find that obscured star-formation of sources with IR luminosities of $\log(L_{\text{IR}}/L_{\odot}) \gtrsim 11.8$ account for $\approx 60\%$ – 90% of the $z \sim 2$ cosmic star-formation rate density.

Key words: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — submillimeter: galaxies

1 Introduction

Revealing cosmic star formation history is one of the biggest challenges in astronomy. Because a significant fraction of star formation is obscured by dust at high redshifts (e.g., Madau & Dickinson 2014 for a review), infrared (IR)–submillimeter/millimeter (submm/mm) observations are required to understand the true star-forming activity. The intensity of the extragalactic background light (EBL) in the IR–submm/mm range is known to be comparable to that of the EBL in the optical, also showing the importance of IR–submm/mm observations for revealing the dust-obscured activity in the Universe. Deep surveys at submm/mm ($850\ \mu\text{m}$ and $1\ \text{mm}$ wavelengths) with ground-based telescopes uncovered a population of bright ($S_{1\ \text{mm}} \gtrsim 1\ \text{mJy}$) submm/mm galaxies (SMGs; Blain et al. 2002; Casey et al. 2014 for reviews). SMGs are highly obscured by dust, and the resulting thermal dust emission dominates the bolometric luminosity. The energy source of submm/mm emission is primarily from intense star formation activity, with IR luminosities of $L_{\text{IR}} \gtrsim$ a few $\times 10^{12} L_{\odot}$ and star

formation rates of $SFR \gtrsim$ a few $\times 100 M_{\odot}\ \text{yr}^{-1}$. The redshift distribution of SMGs is characterized by a median redshift of $z \sim 2\text{--}3$ (e.g., Chapman et al. 2005; Yun et al. 2012; Simpson et al. 2014; Chen et al. 2016; Michałowski et al. 2017; Brisbin et al. 2017). The stellar masses and SFRs of SMGs show that they are located above or at the massive end of the main sequence of star-forming galaxies (e.g., Daddi et al. 2007; Michałowski et al. 2012, 2014; da Cunha et al. 2015). It is thought that SMGs are progenitors of massive elliptical galaxies in the present-day Universe observed during their formation phase (e.g., Lilly et al. 1996; Smail et al. 2004). The contribution of SMGs to the EBL is estimated by integrating the number counts. Blank field surveys with single-dish telescopes resolved $\sim 20\%$ – 40% of the EBL at $850\ \mu\text{m}$ (e.g., Barger et al. 1999; Eales et al. 2000; Borys et al. 2003; Coppin et al. 2006) and $\sim 10\%$ – 20% at $1\ \text{mm}$ (e.g., Greve et al. 2004; Perera et al. 2008; Scott et al. 2008, 2010; Hatsukade et al. 2011). It is expected that deeper submm/mm observations trace fewer dust-obscured star-forming galaxies, which may overlap galaxies detected in rest-frame ultraviolet (UV) and optical

wavelengths. Whitaker et al. (2017) found a dependence of the fraction of obscured star formation (SFR_{IR}) on stellar mass out to $z = 2.5$: 50% of star formation is obscured for galaxies with $\log(M/M_{\odot}) = 9.4$, and >90% for galaxies with $\log(M/M_{\odot}) > 10.5$. Deep surveys probing fainter submm objects ($S_{1\text{mm}} < 1\text{ mJy}$), which are expected to be more normal star-forming galaxies rather than “classical” SMGs, are essential to understanding the cosmic star-formation history and the origin of EBL; however, such observations have been hampered by the confusion limit of observations with single-dish telescopes since they have large beam sizes ($\sim 15''\text{--}30''$).

Interferometric observations enable us to reveal faint submm sources by substantially reducing the confusion limit. The Atacama Large Millimeter/submillimeter Array (ALMA) is now detecting submm sources more than an order of magnitude fainter than “classical” SMGs. Because of its high sensitivity and high angular resolution, ALMA can collect serendipitous sources from a variety of data sets to probe the fainter end of the number counts (Hatsukade et al. 2013; Ono et al. 2014; Carniani et al. 2015; Fujimoto et al. 2016; Oteo et al. 2016). These studies show that more than 50% of the EBL at 1 mm is resolved into discrete sources at a flux limit of $\sim 0.1\text{ mJy}$.

These studies are based on serendipitous sources detected in fields where faint submm sources are not the main targets, which could introduce biases due to the clustering of sources around the targets or sidelobes caused by bright targets. It is necessary to conduct “unbiased” surveys in a contiguous field rather than collecting discrete fields in order to obtain a survey of the population of faint submm sources. Surveys in a contiguous field are also beneficial to clustering analysis. During ALMA Cycle 1, the central 2 arcmin² area of the Subaru/XMM-Newton Deep Survey Field (SXDF) was observed as an ALMA deep blank field survey (Tadaki et al. 2015; Kohno et al. 2016; Hatsukade et al. 2016; Wang et al. 2016; Yamaguchi et al. 2016). From Cycle 1 to the present, the GOODS-S/Hubble Ultra Deep Field (HUDF) has been observed with ALMA in different surveys (Walter et al. 2016; Aravena et al. 2016; Dunlop et al. 2017; Franco et al. 2018). There are also deep surveys in overdense regions, such as the ALMA deep field in the $z = 3.09$ protocluster SSA 22 field (ADF22: Umehata et al. 2015, 2017, 2018) and the ALMA Frontier Fields Survey of gravitational lensing clusters (González-López et al. 2017).

The GOODS-S/HUDF field has the deepest multi-wavelength data from X-ray to radio with ground-based telescopes and satellites, such as Chandra (Xue et al. 2011; Luo et al. 2017), XMM-Newton (Comastri et al. 2011), HST/ACS/WFC3 (HUDF, CANDELS, XDF: Beckwith et al. 2006; Grogin et al. 2011; Koekemoer et al. 2011; Ellis et al. 2013; Illingworth et al. 2013), VLT/HAWK-I (HUGS:

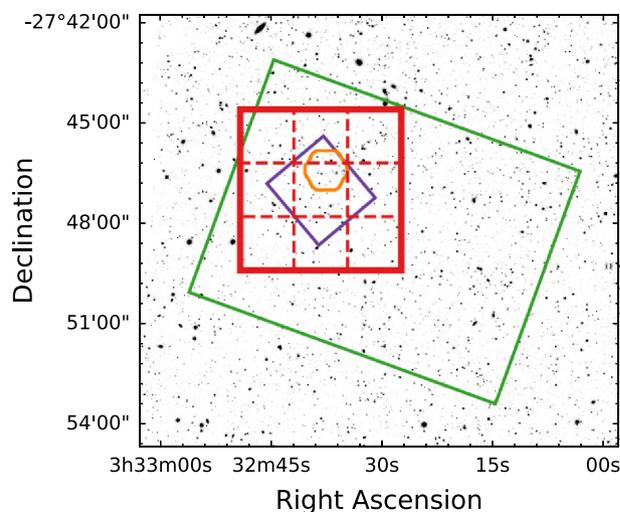


Fig. 1. ASAGAO region consisting of nine subregions (red) overlaid on the HST/WFC3 *F160W* image. The orange, purple, and green regions represent the ALMA survey areas of ASPECS (Walter et al. 2016; Aravena et al. 2016) at 1.2 mm, HUDF (Dunlop et al. 2017) at 1.3 mm, and GOODS-ALMA (Franco et al. 2018) at 1.1 mm, respectively. (Color online)

Fontana et al. 2014), Magellan/FourStar (ZFOURGE: Straatman et al. 2016), Spitzer (S-CANDELS: Ashby et al. 2015), Herschel/PACS (PEP: Lutz et al. 2011) and SPIRE (HerMES: Oliver et al. 2012), APEX/LABOCA (LESS: Weiß et al. 2009), ASTE/AzTEC (Scott et al. 2010; Yun et al. 2012), SCUBA-2/JCMT (Cowie et al. 2017), and VLA (Miller et al. 2013; Rujopakarn et al. 2016). Spectroscopic observations have also been conducted extensively (e.g., Le Fèvre et al. 2004; Brammer et al. 2012; Skelton et al. 2014). The VLT/MUSE spectroscopic survey of HUDF (the $3' \times 3'$ deep region and $1' \times 1'$ ultra-deep region) provides three-dimensional data cubes of this field (Bacon et al. 2015, 2017). JWST will conduct deep multi-band imaging and spectroscopy, offering the ability to diagnose optically faint galaxies, which are difficult of study with existing optical/near-IR telescopes.

The ALMA surveys of the GOODS-S field have been conducted with different survey strategies: a deep but narrow survey (4.5 arcmin^2 , 1σ depth = $34\ \mu\text{Jy beam}^{-1}$) at 1.3 mm (HUDF: Dunlop et al. 2017), a shallower and wider survey (69 arcmin^2 , 1σ depth $\sim 180\ \mu\text{Jy beam}^{-1}$) at 1.1 mm (GOODS-ALMA: Franco et al. 2018), and spectral scans in an area of 1 arcmin^2 (ALMA Spectroscopic Survey: ASPECS) at 3 mm and 1.2 mm (Walter et al. 2016; Aravena et al. 2016)—see figure 1. The spectral scans cover the full window of the bands, offering the deepest continuum maps ($1\sigma_{3\text{mm}} = 3.8\ \mu\text{Jy beam}^{-1}$ and $1\sigma_{1.2\text{mm}} = 12.7\ \mu\text{Jy beam}^{-1}$).

The faint submm sources detected in these studies are found to be on the main sequence, but located at higher stellar mass and SFR ranges (e.g., Hatsukade et al. 2015;

Yamaguchi et al. 2016; Aravena et al. 2016; Dunlop et al. 2017) due to the survey detection limit. In addition, the numbers of sources studied in these surveys are still very limited, and the demand for deeper and wider surveys remains high. In this paper, we present the results of the ALMA twenty-six arcmin² survey of GOODS-S at one millimeter (ASAGAO). ASAGAO is a deep ($1\sigma \sim 61 \mu\text{Jy beam}^{-1}$ for a $250 \text{ k}\lambda$ -tapered map) and wide-area (26 arcmin^2) survey on a contiguous field at 1.2 mm. The observing area matches the deepest VLA C-band 5 cm (6 GHz) observations (Rujopakarn et al. 2016; W. Rujopakarn et al. in preparation) and the ultra-deep VLT/HAWK-I K_s -band images. The primary goal of this survey is to obtain a complete list of galaxies with $L_{\text{IR}} \gtrsim 3 \times 10^{11} L_{\odot}$ or $SFR \gtrsim 50 M_{\odot} \text{ yr}^{-1}$ to help us to understand the dust-obscured star-formation history of the Universe. The initial results based on the ASAGAO data have been reported by Ueda et al. (2018) for the X-ray active galactic nucleus (AGN) properties, and by Fujimoto et al. (2018) for morphological studies. The results of the multi-wavelength analysis are discussed in Yamaguchi et al. (2018), and the clustering analysis has been conducted by Y. Yoshimura et al. (in preparation).

The organization of this paper is as follows. Section 2 outlines the ALMA observations, data reduction, and archival data used in this study, and shows the images obtained. Section 3 describes the detected sources, and we list the source catalog. In section 4 we describe the method of creating number counts, and compare the present study with previous one. We present the method of constructing luminosity functions and compare with previous studies in section 5.1. The conclusions are presented in section 6. Throughout the paper, we adopt a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$, and a Chabrier (2003) initial mass function (IMF). All magnitudes are given in the AB system.

2 Observations and data reduction

2.1 Observations

ALMA band 6 observations of the GOODS-S field were conducted in 2016 September 02–29 for the Cycle 3 program (Project code: 2015.1.00098.S, PI: K. Kohno) as summarized in table 1. The $\sim 5' \times 5'$ survey area centered at (RA, Dec) = ($03^{\text{h}}31^{\text{m}}38^{\text{s}}.601$, $-27^{\circ}46'59''.830$) consists of nine tiles (figure 1), and each tile was covered by ~ 90 -pointing mosaic observations with Nyquist sampling. Two frequency tunings were adopted to cover a wider frequency range, providing a larger survey volume for searching serendipitous line-emitting galaxies. The center frequencies of the tunings are 262.56 GHz (1.14 mm) and 253.56 GHz (1.18 mm),

Table 1. ALMA observations.

Date	Tuning	Subregion	N_{ant}	Baseline (max) (m)
2016-09-02	2	NW	39, 45	1808.012, 2732.660
2016-09-03	2	NE	41	1770.782
2016-09-06	2	NE	39	2483.450
2016-09-07	1	N	39	2483.450
2016-09-08	2	SW	39	2483.450
2016-09-12	2	SE	38	3143.756
2016-09-14	2	SE	38	3247.644
2016-09-18	1, 2	NW, W	38	2483.451
2016-09-19	2	W	40	3143.756
2016-09-20	1, 2	E	39	3143.756
2016-09-21	1, 2	E, SW, S	39	3143.756
2016-09-22	1, 2	SW, S	39	3143.756
2016-09-24	2	N, C	39	3143.756
2016-09-25	1, 2	C, NE	39	3143.756
2016-09-26	1	NE, C	40	3247.644
2016-09-27	1	W, C	43	3247.644
2016-09-28	1	W, S, SE	40	3143.756
2016-09-29	1	SE	39	3247.644

Table 2. Center frequencies of spectral windows used in the surveys of ASAGAO, HUDF, and GOODS-ALMA.

spw ID	ASAGAO		HUDF*	GOODS-ALMA*
	Tuning 1 (GHz)	Tuning 2 (GHz)		
0	254.12	245.12	212.2	255.9
1	256.00	247.00	214.2	257.9
2	269.12	260.12	228.2	271.9
3	271.00	262.00	230.2	273.9

*HUDF: Dunlop et al. (2017); GOODS-ALMA: Franco et al. (2018).

which were selected to avoid strong atmospheric absorption lines (table 2 and figure 2). The correlator was used in the time domain mode (TDM). Four basebands were used for each tuning, and a spectral window (spw) was placed for each baseband with a bandwidth of 2000 MHz ($15.625 \text{ MHz} \times 128$ channels), providing a total nominal bandwidth of 16 GHz (effective bandwidth of 15 GHz) centered at 258.6 GHz (1.16 mm). The observations were done in 37 execution blocks in the C40-6 array configuration (maximum recoverable scale of $\theta_{\text{MRS}} \approx 1''.2$) with a minimum baseline length of 15.065 m and a maximum baseline length ranging from 1770 m to 3247 m. The number of available antennas was 38–45. The total observing time is 45 hr, and the on-source integration time is 29 hr. The bandpass was calibrated with quasars J0522–3627, J0238+1636, and J0334–4008, and the phase was calibrated with J0348–2749, J0334–4008 and J2357–5311 were observed as flux calibrators.

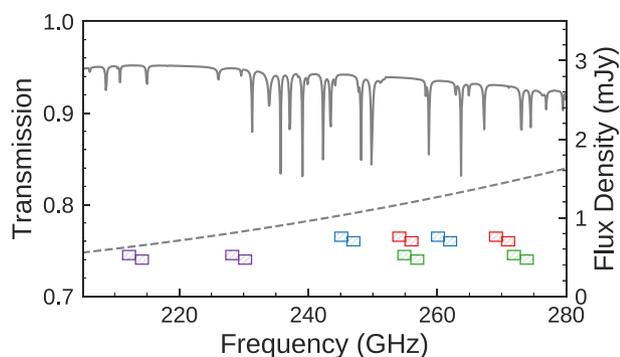


Fig. 2. Frequency setups of ASAGAO tuning 1 (red), tuning 2 (blue), HUDF (purple), and GOODS-ALMA (green). The solid line represents the atmospheric transmission at the ALMA site for a precipitable water vapor of 1 mm calculated by using the Atmospheric Transmission at Microwaves code¹ (ATM: Pardo et al. 2001; left-hand axis). The dashed line shows the modified black body spectrum with a dust emissivity index of $\beta = 1.5$, a dust temperature of 35 K, and $z = 2$, scaled to a flux density at 243 GHz of 1 mJy (right-hand axis). (Color online)

2.2 Data reduction

To reduce the data volume for easier handling in continuum imaging, we average the data in frequency and time directions with 32 channels ($\Delta\nu = 0.5$ GHz) and 10.08 s, respectively. The effect of bandwidth smearing on the peak flux density of a source caused by the channel averaging is less than 1% even at the edge of the primary beam (Condon et al. 1998). We also confirm that the effect of the time averaging on the flux density is negligible based on the imaging of the bandpass calibrator.

The data were reduced with Common Astronomy Software Applications (CASA: McMullin et al. 2007). Data calibration was done with the ALMA Science Pipeline Software of CASA version 4.7.2. The maps were processed

by the task `tclean` of CASA version 5.1.1 with natural weighting, a cell size of $0''.1$, a gridding option of `standard`, the spectral definition mode of multi-frequency synthesis, the number of Taylor coefficients in the spectral model of 2 for a spectrum with a slope, and a primary beam limit of 0.2 (default value). Clean boxes are placed when a component with a peak signal-to-noise ratio (S/N) above 5 is identified, and CLEANed down to a 2σ level. Because the observations were done with a higher angular resolution ($\sim 0''.2$) than requested because of the restriction of array configuration, we adopt a uv -taper of $250\text{ k}\lambda$ to weight extended components, which gives a synthesized beam size of $0''.51 \times 0''.45$. The signal-to-noise ratio map and the primary beam coverage map are shown in figure 3. In this study, we use the region where the primary beam coverage is larger than, or equal to, 0.2 in the map, which is a 26 arcmin^2 area. A sensitivity map was created by using the BANE program (Hancock et al. 2012), which performs 3σ clipping in the signal map, calculates the standard deviation on a sparse grid of pixels, and then interpolates to make a noise image. Figure 4 shows the histograms of flux density of the signal map (before primary beam correction). The pixel-flux distribution is well explained by a Gaussian curve, and a Gaussian fit gives 1σ of $61\ \mu\text{Jy beam}^{-1}$. The excess from the fitted Gaussian at $\gtrsim 0.3\text{ mJy}$ indicates the contribution from real sources.

2.3 ALMA archival data

In addition to our data, we also use the ALMA archival data of 1 mm (band 6) surveys in the GOODS-S field of HUDF (Dunlop et al. 2017) and GOODS-ALMA (Franco et al. 2018). We do not use the data set of ASPECS, where the

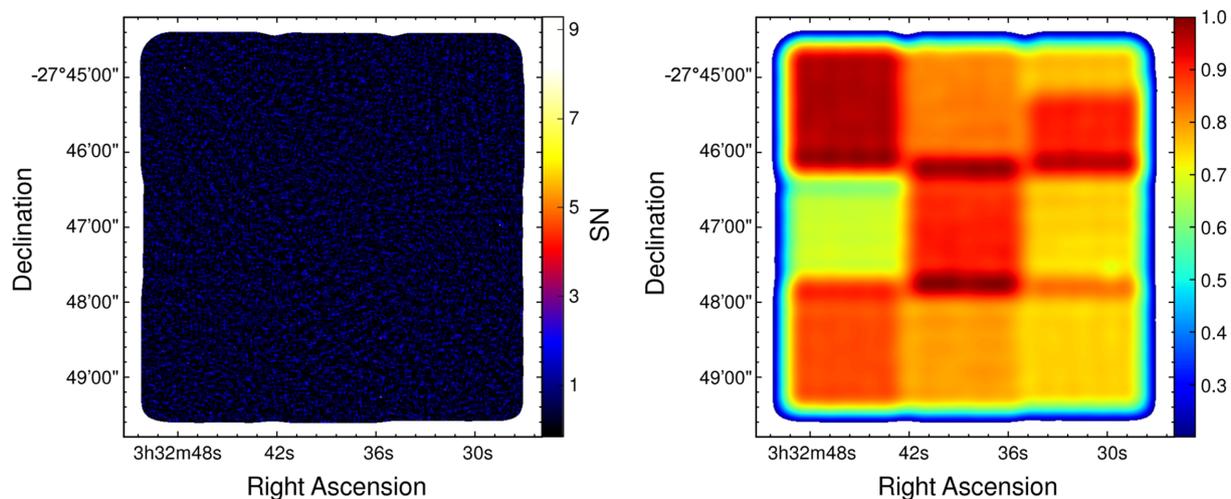


Fig. 3. Signal-to-noise ratio map with a $250\text{ k}\lambda$ taper (left) and the primary beam coverage map (right) based on the original ASAGAO data. (Color online)

¹ (<https://almascience.eso.org/about-almatamosphere-model>).

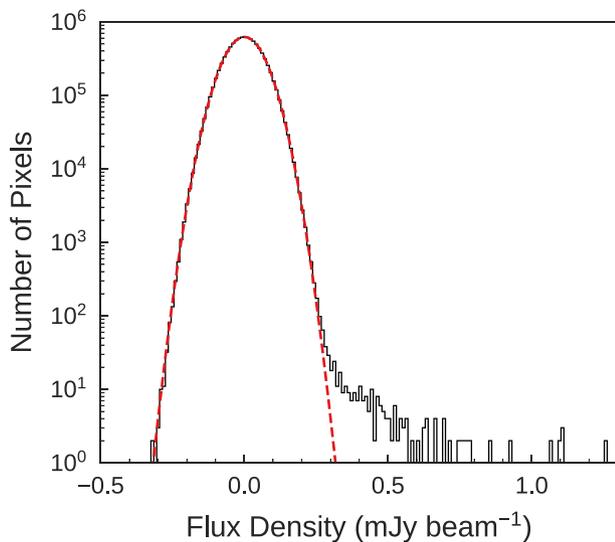


Fig. 4. Distribution of flux density of the signal map based on the original ASAGAO data (uncorrected for primary beam attenuation). The dashed curve shows the result of a Gaussian fit ($1\sigma = 61 \mu\text{Jy beam}^{-1}$). (Color online)

synthesized beam size ($1''.68 \times 0''.92$) is largely different from those of the others ($\lesssim 0''.5$).

The ALMA survey of HUDF by Dunlop et al. (2017) covered a 4.5 arcmin^2 area at 1.3 mm during Cycle 1 and Cycle 2 (Project code: 2012.1.00173.S, PI: J. Dunlop). The correlator was configured with four spectral windows with a 2000 MHz bandwidth ($15.625 \text{ MHz} \times 128$ channels). The synthesized beam with natural weighting is $0''.59 \times 0''.50$. A uv -tapering of $\simeq 220 \times 180 \text{ k}\lambda$ they adopted gives a final synthesized beam of $0''.71 \times 0''.67$ and a noise level of $34 \mu\text{Jy beam}^{-1}$.

A wider area of 69 arcmin^2 ($\sim 10' \times 7'$) was observed in the GOODS-ALMA survey (Franco et al. 2018) at 1.13 mm during Cycle 3 (Project code: 2015.1.00543.S, PI: D. Elbaz). The survey consists of six submosaics, encompassing the survey fields of ASAGAO, HUDF, and ASPECS. The correlator was set to have four spectral windows with $15.625 \text{ MHz} \times 128$ channels. The synthesized beam with natural weighting is $\sim 0''.20$ – $0''.29$ depending on the sub-regions. The rms noise levels are $\sim 180 \mu\text{Jy beam}^{-1}$ and $\sim 110 \mu\text{Jy beam}^{-1}$ for the tapered map with a synthesized beam of $0''.6$ and for the untapered map, respectively.

2.4 Combined map

The archival data sets of HUDF (Dunlop et al. 2017) and GOODS-ALMA (Franco et al. 2018) are combined with the original ASAGAO data to make a deeper map with a total effective frequency coverage of $\sim 27 \text{ GHz}$ (table 2 and figure 2). Before combining the data sets, we relabel the coordinates of Cycle 1 and Cycle 2 data from J2000.0

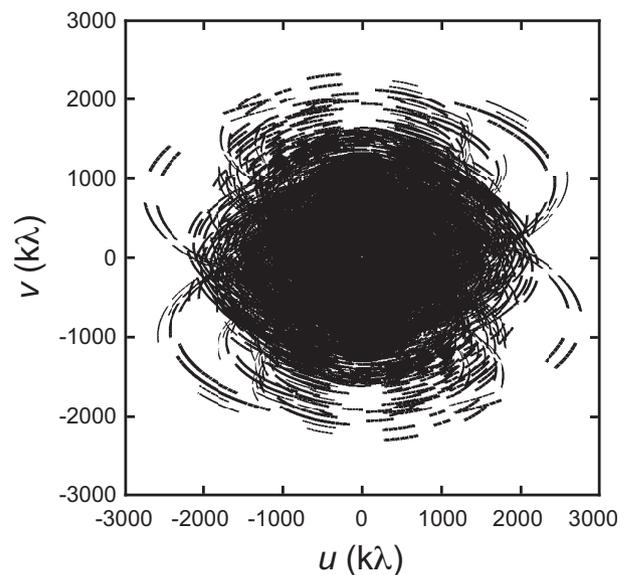


Fig. 5. uv -plane coverage of the combined data.

to the International Celestial Reference System (ICRS) by using a CASA script offered by the ALMA project, because the position reference frame in ALMA uv data and images is given as J2000.0 before Cycle 3 and as ICRS since Cycle 3. The uv data sets are averaged in frequency and time directions (32 channels and 10.08 s) in the same manner as the original ASAGAO data. Figure 5 shows the uv -plane coverage of the combined data. The combined map was produced with CASA with the same parameters adopted in subsection 2.2. The representative frequency of the map is 243.047 GHz (1.23 mm). We adopt a uv -taper of $250 \text{ k}\lambda$ to weight extended components, which gives a final synthesized beam size of $0''.59 \times 0''.53$. Maps without uv -taper (synthesized beam size of $0''.30 \times 0''.24$) and with a uv -taper of $160 \text{ k}\lambda$ ($0''.83 \times 0''.72$) were also created to see whether detected sources are spatially resolved. The signal map, the coverage map, and the rms noise map (corrected for primary beam attenuation) with a $250 \text{ k}\lambda$ taper are shown in figures 6 and 7. We use the same region as adopted in the original ASAGAO map (subsection 2.2). The map has two layers, the central deeper area (the deepest region has $1\sigma \sim 26 \mu\text{Jy beam}^{-1}$) and the rest, as can be seen in figure 7, and figure 8 of the cumulative area as a function of rms noise level.

Figure 9 shows the histogram of flux density of the signal map (before primary beam correction). The dashed curve represents the result of a Gaussian fit, which gives 1σ of $34 \mu\text{Jy beam}^{-1}$. The presence of real sources in the map makes an excess of positive pixels. This fit also deviates from the distribution of pixel values at high negative flux densities, which can be explained by the non-uniform noise distribution of the entire map.

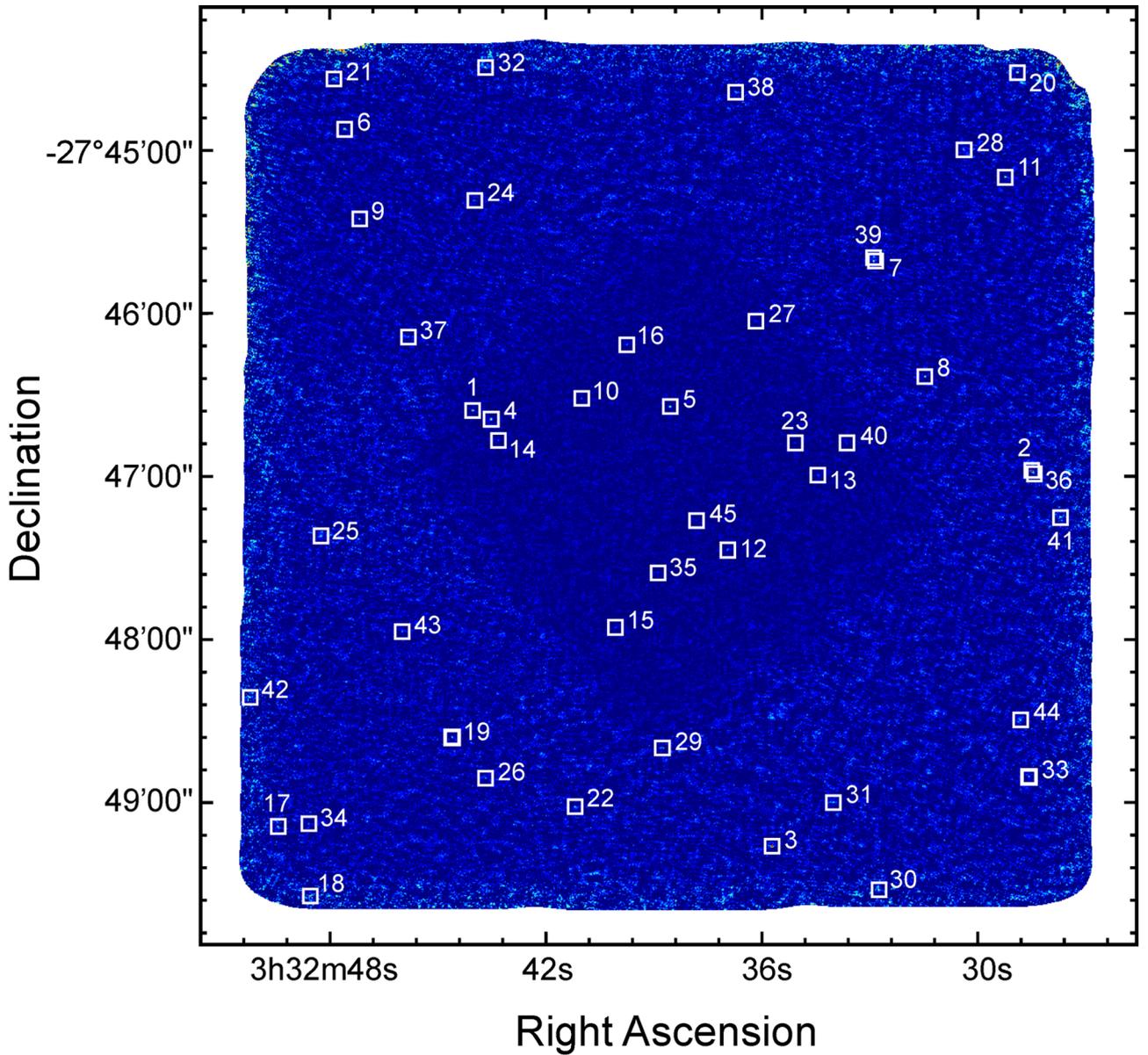


Fig. 6. Combined signal map (ASAGAO + HUDF + GOODS-ALMA) with a 250 k λ taper (corrected for primary beam attenuation). The squares represent the detected sources. (Color online)

3 Source catalog

3.1 Source detection

Source detection is conducted on the signal map before correcting for the primary beam attenuation. We adopt the source-finding algorithm called AEGEAN (Hancock et al. 2012, 2018), which achieves high reliability and completeness performance for radio maps. The background and noise estimation are done with the BANE package in the same manner as described in subsection 2.2. We find 25 (45) sources with a peak S/N of $\geq 5\sigma$ ($\geq 4.5\sigma$). The detected sources are fitted with a two-dimensional elliptical Gaussian to estimate the source size and integrated flux

density. The integrated flux density (S_{int}) is calculated as

$$S_{\text{int}} = S_{\text{peak}} \frac{ab}{\theta_{\text{maj}}\theta_{\text{min}}}, \quad (1)$$

where S_{peak} is the peak flux density, a/b are the fitted major/minor axes, and $\theta_{\text{maj}}/\theta_{\text{min}}$ are the synthesized beam major/minor axes. We adopt S_{int} as the source flux density. When $S_{\text{int}} < S_{\text{peak}}$, we adopt S_{peak} , since it is possible that the source fitting failed due to the low S/N .

The source catalog for the 4.5σ sources extracted in the combined signal map with a 250 k λ taper is presented in table 3. Hereafter we refer to these sources as ASAGAO

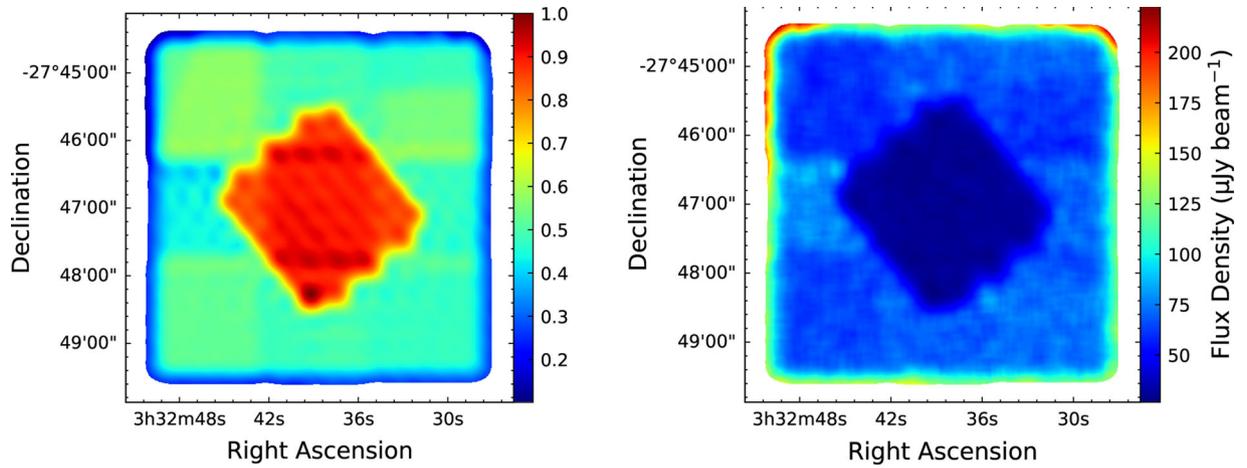


Fig. 7. Primary beam coverage map (left) and the rms noise map (right) for the combined data. The rms noise map is corrected for primary beam attenuation. (Color online)

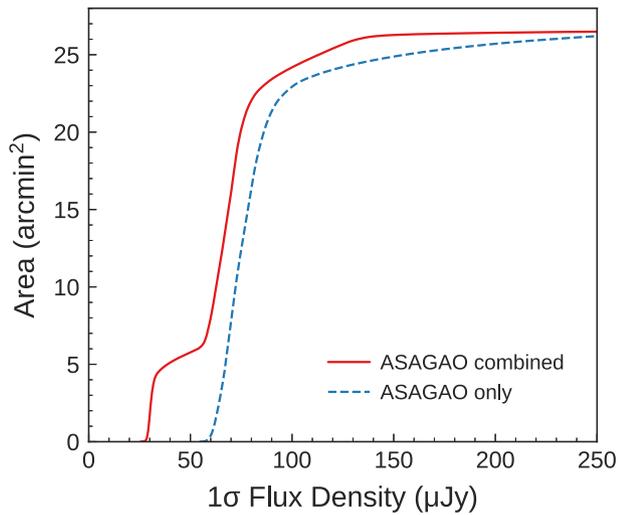


Fig. 8. Cumulative area of the combined map as a function of rms noise level (corrected for primary beam attenuation) for the ASAGAO only data (dashed) and the combined data (solid). (Color online)

sources, and adopt the integrated flux densities measured in the 250 k λ -tapered map. The range of continuum flux densities is 0.16–2 mJy (after correcting for primary beam attenuation). The integrated flux densities in the untapered map ($S_{\text{int}}^{\text{untaper}}$) and in the map with a 160 k λ taper ($S_{\text{int}}^{160\text{k}\lambda}$) measured in the same manner as in the 250 k λ -tapered map are also shown. When a source is not detected with a peak $S/N > 3$ in these maps, the flux density is not listed in the source catalog. ASAGAO ID31, 36, and 37 are not detected in the untapered map with a peak $S/N > 3$. This can be due to the lack of sensitivity for spatially extended structures or clumpy structures and multiple peaks, as can be seen in the postage-stamp images in figure 10, each having a peak S/N less than 3. The median ratio between integrated flux and peak flux is $S_{\text{int}}/S_{\text{peak}} = 1.3 \pm 0.8$. The median ratio of integrated flux between the 250 k λ -tapered map and

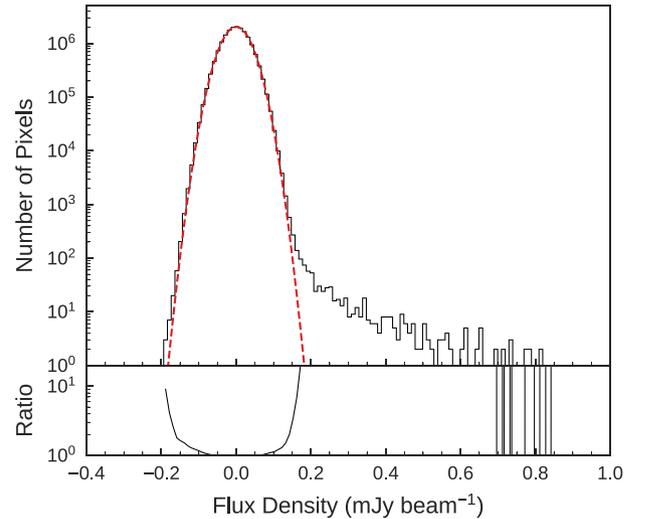


Fig. 9. Top: Distribution of flux density of the signal map based on the combined data (uncorrected for primary beam attenuation). The dashed curve shows the result of a Gaussian fit ($1\sigma = 34 \mu\text{Jy beam}^{-1}$). Bottom: Ratio between the flux density distribution and the result of a Gaussian fit. (Color online)

160 k λ -tapered map or the untapered map is $S_{\text{int}}^{250\text{k}\lambda}/S_{\text{int}}^{160\text{k}\lambda} = 0.86 \pm 0.24$, and $S_{\text{int}}^{250\text{k}\lambda}/S_{\text{int}}^{\text{untaper}} = 1.3 \pm 3.0$. These suggest that sources are resolved by the synthesized beam in the 250 k λ -tapered and untapered maps.

In order to estimate the degree of contamination by spurious sources, we count the number of negative peaks as a function of S/N threshold (figure 11). The number of independent beams in the map is 2.7×10^5 , and the expected number of $\geq 4.5\sigma$ sources in a Gaussian statistic is ~ 1 . However, it is reported that this estimation underestimates the negative peaks in previous studies based on ALMA images (Dunlop et al. 2017; Vio & Andreani 2016; Vio et al. 2017). The actual number of negative peaks in the combined map is one at $\geq 5\sigma$ and eight at 4.5σ – 5σ .

Table 3. Source catalog of $\geq 5\sigma$ sources (ID1–25) and 4.5σ – 5σ sources (ID26–45).*

ID	RA (J2000.0)	Dec (J2000.0)	S/N	S_{peak} (μJy)	S_{int} (μJy)	$S_{\text{int}}^{\text{untaper}}$ (μJy)	$S_{\text{int}}^{160\text{k}\lambda}$ (μJy)	Note
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	03 ^h 32 ^m 44 ^s .03	−27°46′35″.97	26.0	839 ± 32	990 ± 36	877 ± 32	1023 ± 44	UDF1, AGS6, U3
2	03 ^h 32 ^m 28 ^s .51	−27°46′58″.36	25.6	1851 ± 72	1983 ± 75	1996 ± 57	2251 ± 112	AGS1, U1
3	03 ^h 32 ^m 35 ^s .72	−27°49′16″.27	24.0	1656 ± 69	1758 ± 70	1816 ± 54	1709 ± 100	AGS3, U2
4	03 ^h 32 ^m 43 ^s .53	−27°46′39″.25	21.0	658 ± 31	914 ± 41	761 ± 40	1019 ± 50	UDF2, AGS18, U6
5	03 ^h 32 ^m 38 ^s .55	−27°46′34″.61	18.1	554 ± 31	745 ± 39	634 ± 35	791 ± 45	UDF3, ASPECS/C1, AGS12, U8
6	03 ^h 32 ^m 47 ^s .59	−27°44′52″.43	12.4	768 ± 62	954 ± 74	735 ± 43	1161 ± 123	U4
7	03 ^h 32 ^m 32 ^s .90	−27°45′41″.07	8.8	546 ± 63	829 ± 86	593 ± 65	835 ± 104	U5
8	03 ^h 32 ^m 31 ^s .48	−27°46′23″.50	8.7	576 ± 66	650 ± 72	618 ± 57	705 ± 103	AGS13, U12
9	03 ^h 32 ^m 47 ^s .18	−27°45′25″.48	8.6	495 ± 57	488 ± 55	945 ± 106	406 ± 69	
10	03 ^h 32 ^m 41 ^s .02	−27°46′31″.59	8.6	255 ± 30	278 ± 31	350 ± 39	246 ± 32	UDF4
11	03 ^h 32 ^m 29 ^s .25	−27°45′09″.96	8.5	580 ± 68	678 ± 78	587 ± 51	855 ± 124	
12	03 ^h 32 ^m 36 ^s .96	−27°47′27″.14	7.4	227 ± 31	408 ± 49	190 ± 35	484 ± 61	UDF5
13	03 ^h 32 ^m 34 ^s .44	−27°46′59″.86	7.2	224 ± 31	436 ± 53	227 ± 34	503 ± 65	UDF6
14	03 ^h 32 ^m 43 ^s .33	−27°46′46″.96	7.2	229 ± 32	259 ± 35	224 ± 26	281 ± 48	UDF7, U7
15	03 ^h 32 ^m 40 ^s .07	−27°47′55″.72	6.6	197 ± 30	458 ± 64	166 ± 32	490 ± 69	UDF11
16	03 ^h 32 ^m 39 ^s .75	−27°46′11″.67	6.5	192 ± 29	539 ± 65	106 ± 22	640 ± 76	UDF8, ASPECS/C2
17	03 ^h 32 ^m 49 ^s .45	−27°49′09″.00	6.1	516 ± 83	564 ± 90	485 ± 55	1286 ± 289	U11
18	03 ^h 32 ^m 48 ^s .57	−27°49′34″.62	5.8	749 ± 130	1091 ± 172	353 ± 94	1868 ± 370	
19	03 ^h 32 ^m 44 ^s .61	−27°48′36″.13	5.7	375 ± 67	434 ± 73	345 ± 51	431 ± 99	U10
20	03 ^h 32 ^m 28 ^s .91	−27°44′31″.54	5.6	614 ± 109	653 ± 110	637 ± 80	749 ± 187	
21	03 ^h 32 ^m 47 ^s .90	−27°44′33″.96	5.5	499 ± 91	1011 ± 178	356 ± 57	3116 ± 536	
22	03 ^h 32 ^m 41 ^s .20	−27°49′01″.75	5.4	371 ± 68	612 ± 101	187 ± 43	797 ± 153	
23	03 ^h 32 ^m 35 ^s .09	−27°46′47″.82	5.4	163 ± 30	206 ± 37	135 ± 20	202 ± 44	UDF13
24	03 ^h 32 ^m 43 ^s .99	−27°45′18″.74	5.0	299 ± 60	446 ± 82	65 ± 120	482 ± 102	
25	03 ^h 32 ^m 48 ^s .24	−27°47′22″.14	5.0	385 ± 77	858 ± 223	186 ± 46	1168 ± 186	
26	03 ^h 32 ^m 43 ^s .68	−27°48′51″.12	4.9	314 ± 64	254 ± 52	286 ± 37	364 ± 91	
27	03 ^h 32 ^m 36 ^s .17	−27°46′03″.04	4.9	154 ± 32	226 ± 45	170 ± 43	374 ± 80	
28	03 ^h 32 ^m 30 ^s .41	−27°44′59″.97	4.9	348 ± 72	716 ± 154	124 ± 34	888 ± 184	
29	03 ^h 32 ^m 38 ^s .74	−27°48′40″.12	4.8	348 ± 71	227 ± 46	551 ± 84	677 ± 185	
30	03 ^h 32 ^m 32 ^s .76	−27°49′32″.41	4.7	578 ± 122	886 ± 180	452 ± 123	1157 ± 253	
31	03 ^h 32 ^m 34 ^s .02	−27°49′00″.11	4.7	339 ± 72	846 ± 158	—	881 ± 173	
32	03 ^h 32 ^m 43 ^s .68	−27°44′29″.66	4.7	461 ± 98	769 ± 164	299 ± 56	1140 ± 249	
33	03 ^h 32 ^m 28 ^s .59	−27°48′50″.57	4.7	347 ± 74	366 ± 79	283 ± 42	425 ± 108	
34	03 ^h 32 ^m 48 ^s .60	−27°49′07″.95	4.6	298 ± 65	313 ± 67	303 ± 52	328 ± 80	
35	03 ^h 32 ^m 38 ^s .89	−27°47′35″.50	4.6	140 ± 30	180 ± 39	74 ± 18	169 ± 44	
36	03 ^h 32 ^m 28 ^s .46	−27°46′58″.83	4.6	333 ± 73	635 ± 134	—	—	
37	03 ^h 32 ^m 45 ^s .83	−27°46′08″.86	4.6	270 ± 59	362 ± 76	—	1879 ± 405	
38	03 ^h 32 ^m 36 ^s .74	−27°44′38″.73	4.6	334 ± 73	441 ± 91	175 ± 50	1496 ± 309	
39	03 ^h 32 ^m 32 ^s .90	−27°45′39″.37	4.6	286 ± 63	529 ± 107	148 ± 37	833 ± 194	
40	03 ^h 32 ^m 33 ^s .65	−27°46′47″.94	4.6	149 ± 33	198 ± 42	304 ± 66	202 ± 51	
41	03 ^h 32 ^m 27 ^s .72	−27°47′15″.17	4.6	459 ± 99	629 ± 133	229 ± 60	805 ± 188	
42	03 ^h 32 ^m 50 ^s .25	−27°48′21″.16	4.6	588 ± 129	621 ± 137	596 ± 137	885 ± 224	
43	03 ^h 32 ^m 45 ^s .99	−27°47′57″.18	4.6	283 ± 62	495 ± 106	149 ± 42	589 ± 128	
44	03 ^h 32 ^m 28 ^s .84	−27°48′29″.72	4.5	350 ± 77	2051 ± 447	107 ± 25	1679 ± 362	
45	03 ^h 32 ^m 37 ^s .83	−27°47′16″.49	4.5	131 ± 29	157 ± 33	117 ± 25	128 ± 33	

* (1) ASAGAO ID. (2) Right ascension. (3) Declination. (4) Peak signal-to-noise ratio. (5) Peak flux density (corrected for primary beam attenuation). (6) Integrated flux density (corrected for primary beam attenuation). (7) Integrated flux density (corrected for primary beam attenuation) measured in the untapered map when the peak S/N is above 3. (8) Integrated flux density (corrected for primary beam attenuation) measured in the 160 k λ -tapered map when the peak S/N is above 3. (9) Note on source IDs of Dunlop et al. (2017) (UDF), Aravena et al. (2016) (ASPECS), Franco et al. (2018) (AGS), and Ueda et al. (2018) (U).

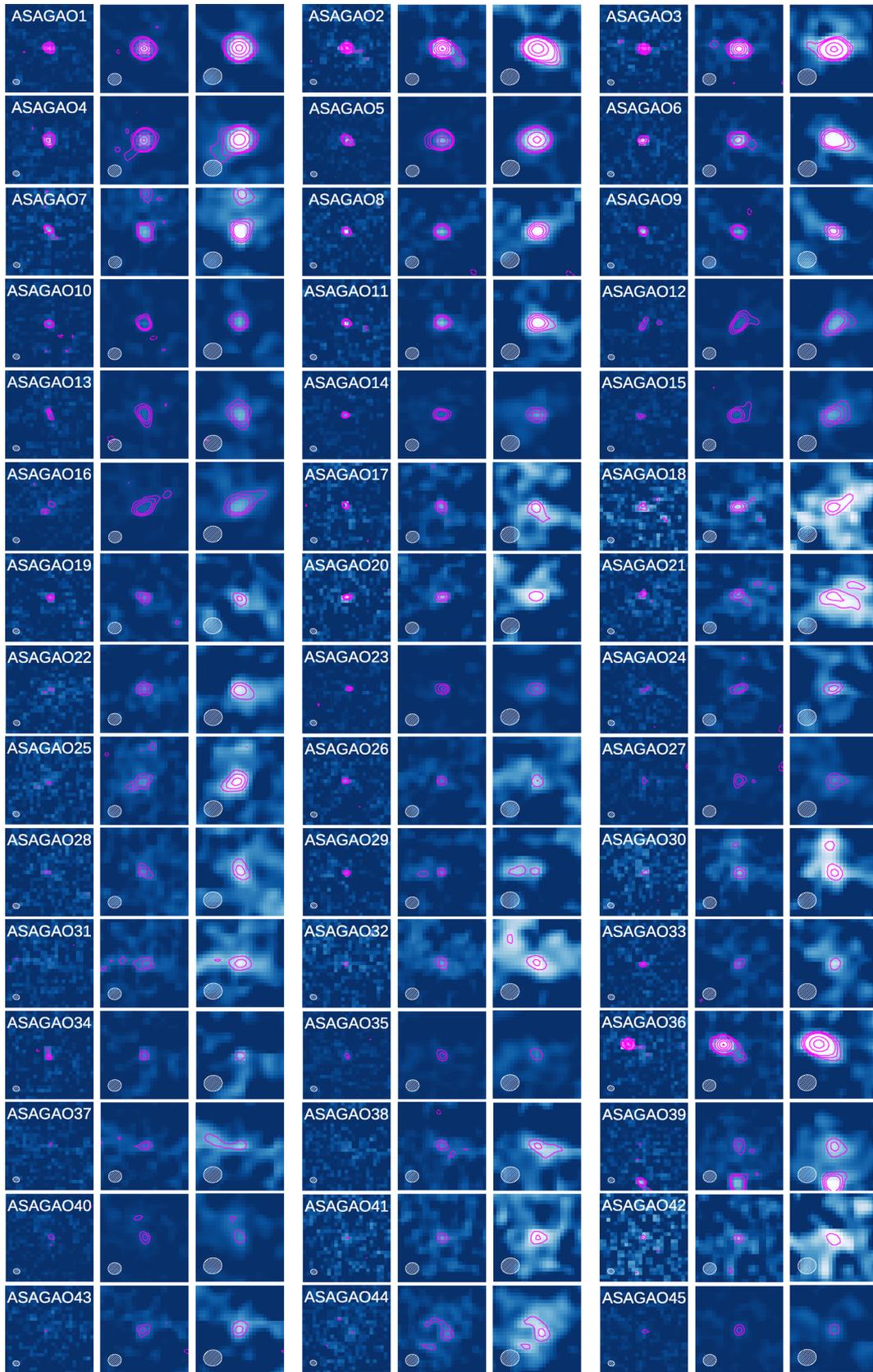


Fig. 10. Postage-stamp images of the ASAGAO $\geq 4.5\sigma$ sources with no taper (left), a 250 $k\lambda$ taper (middle), and a 160 $k\lambda$ taper (right). The image size is $4'' \times 4''$. Contours are 3σ , 4σ , 5σ , and 5σ steps subsequently (negative contours are shown as dashed lines). The synthesized beam size is shown in the lower left-hand corner of each panel. (Color online)

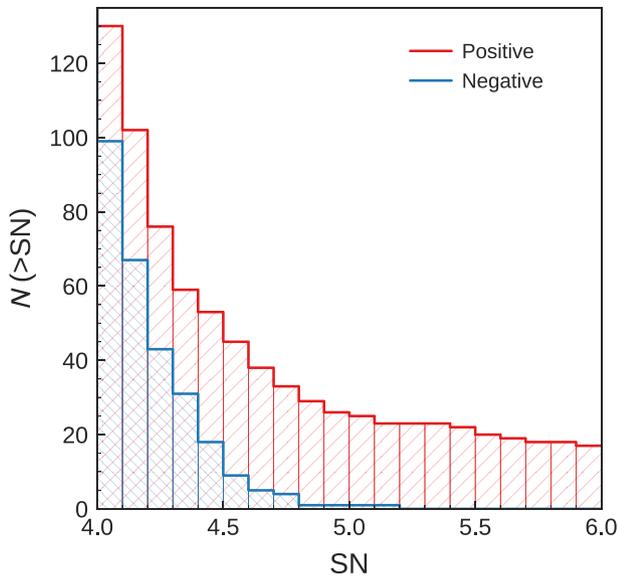


Fig. 11. Cumulative number of positive and negative peaks as a function of peak S/N threshold. (Color online)

The small number of negative peaks at $\geq 5\sigma$ suggests the robustness of the 5σ sources. Actually, 22 out of the 25 sources with a peak of $\geq 5\sigma$ (88%) have counterparts at optical, Spitzer/IRAC, radio, or ALMA $850\ \mu\text{m}$ (Cowie et al. 2018) (see Yamaguchi et al. 2018 for multi-wavelength identifications of ASAGAO sources).

3.2 Astrometry

Calibration for astrometry is performed by interpolating the phase information of the phase calibrators over the target fields. The astrometric accuracy of a source depends on statistical errors, determined by the source S/N and systematic errors such as the atmospheric phase stability, the proximity of an astrometric calibrator, and baseline errors. The minimum obtainable astrometric accuracy with no systematic errors is determined by a source S/N , observing frequency, and maximum baseline length, which gives $\sim 0''.15$ for a 5σ source with the observing frequency of 243.047 GHz and the maximum baseline of 3.2 km (see ALMA Technical Handbook).

To confirm the astrometry of ASAGAO sources, the positions of the 5σ sources are cross-matched with sources detected in the VLA 5 cm survey (Rujopakarn et al. 2016; W. Rujopakarn et al. in preparation). The radio sources are more suitable for evaluating the astrometry of the ALMA sources compared to optical sources, because (i) the angular resolution and positional accuracy are comparable to those of the ALMA observations, and (ii) the positions of submm/mm emission and optical emission, which typically trace dust-obscured and unobscured parts, respectively, do

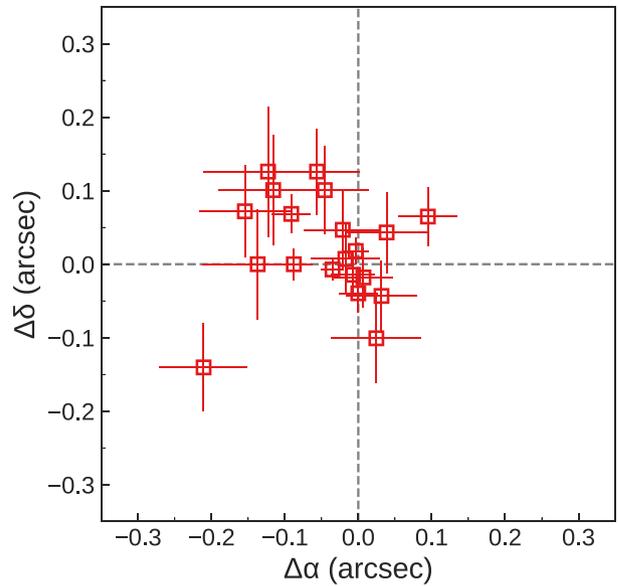


Fig. 12. Positional offsets of the 5σ ASAGAO sources from the VLA 5 cm radio sources (Rujopakarn et al. 2016; W. Rujopakarn et al. in preparation). The errors are the square root of the sum of the squares of expected 1σ positional uncertainties of the ASAGAO and VLA sources. (Color online)

not necessarily coincide within a galaxy, and radio observations can trace dust-obscured parts. The radio counterparts are found for 20 out of the 25 ASAGAO 5σ sources within a $0''.5$ search radius, and the positional offset between them is plotted in figure 12. The median offset is $(\Delta\alpha, \Delta\delta) = (+0''.03 \pm 0''.08, -0''.01 \pm 0''.06)$, which is within the expected positional uncertainty between the ALMA and the radio sources of $\sim 0''.1$ as the square root of the sum of the squares of both uncertainties [$\Delta\alpha = \Delta\delta \simeq 0.6 (S/N)^{-1}$ FWHM; Ivison et al. 2007].

3.3 Comparison with ALMA 1 mm sources in GOODS-S

We cross-matched the ASAGAO sources with the HUDF, GOODS-ALMA, and ASPECS sources (table 3). Dunlop et al. (2017) listed 16 HUDF sources, and we confirmed that all the eight sources with $S/N > 4.5$ out of 16 are detected in our map. Two additional other sources are detected in our map, and the other six sources are not detected due to their lower S/N . Among the 20 GOODS-ALMA sources presented in Franco et al. (2018), we confirmed that all of the six sources inside the ASAGAO region are detected in our map. A comparison of flux densities of sources common with these surveys shows that the median flux ratios are $S_{243\text{ GHz}}^{\text{ASAGAO}}/S_{221\text{ GHz}}^{\text{HUDF}} = 1.15 \pm 0.64$ and $S_{243\text{ GHz}}^{\text{ASAGAO}}/S_{265\text{ GHz}}^{\text{GOODS-ALMA}} = 0.89 \pm 0.13$, which are consistent with the flux ratios assuming a modified black body with a dust emissivity index of $\beta = 1.5$, a dust temperature of

35 K, and $z = 2$ ($S_{243\text{ GHz}}/S_{221\text{ GHz}} = 1.3$ and $S_{243\text{ GHz}}/S_{265\text{ GHz}} = 0.78$). The two brightest sources ($S_{1.2\text{ mm}} > 0.2\text{ mJy}$) of ASPECS, which are the highest S/N sources ($S/N > 10$) in their source catalog, are also detected in our map. The non-detection of lower- S/N ASPECS sources can be explained by their lower flux densities ($S_{1.2\text{ mm}} < 0.15\text{ mJy}$). The ASAGAO 5σ sources without counterpart in the other surveys are outside the regions of ASPECS and HUDF, and have lower flux densities than the detection limit of GOODS-ALMA.

3.4 Comparison with AzTEC sources

The central 270 arcmin^2 area of the GOODS-S field was observed with AzTEC (Wilson et al. 2008), mounted on the Atacama Submillimeter Telescope Experiment (ASTE: Ezawa et al. 2004, 2008) at 1.1 mm (270 GHz ; Scott et al. 2010). The beam size of AzTEC on ASTE is $30''$ (FWHM). Two AzTEC sources identified in Scott et al. (2010), AzTEC/GS18 and 21, are located inside the ASAGAO region, and are detected as multiple sources in our 4.5σ source catalog.

AzTEC/GS18 is detected as three ASAGAO sources (ID1, 4, and 14), and the total flux of the three sources is $S_{1.2\text{ mm}} = 2.16 \pm 0.06\text{ mJy}$, which is consistent with the flux density of the AzTEC source, $S_{1.1\text{ mm}} = 3.2 \pm 0.6\text{ mJy}$ (Downes et al. 2012) taking into account the flux ratio between 1.2 mm and 1.1 mm of $S_{1.2\text{ mm}}/S_{1.1\text{ mm}} \sim 0.73$. Yun et al. (2012) studied the radio and Spitzer counterparts of the AzTEC/GOODS-S sources. They found three counterpart candidates for AzTEC/GS18, two of which are detected in the ASAGAO map. The other is identified in the 1.3 mm source catalog of Dunlop et al. (2017) as a 4.26σ source (UDF9).

AzTEC/GS21 has an ASAGAO counterpart (ID6) within $15''$ of the AzTEC source position. Another source (ID21) is located $\sim 16''$ away from the AzTEC source position. ASAGAO ID6 is identified as a radio and Spitzer counterpart candidate of Yun et al. (2012). The total flux of the two ALMA sources is $S_{1.2\text{ mm}} = 1.97 \pm 0.19\text{ mJy}$, which is also consistent with the flux density of the AzTEC source, $S_{1.1\text{ mm}} = 2.7 \pm 0.6\text{ mJy}$ (Downes et al. 2012), by considering the expected flux ratio between 1.2 mm and 1.1 mm emission.

4 Number counts

Number counts are constructed by using the 45 4.5σ sources. We correct for the effective area where sources are detected at $S/N \geq 4.5$, the contribution of spurious sources,

survey completeness, and flux boosting. In this section, we present the methods of estimating survey completeness and flux boosting (subsection 4.1), and constructing number counts (subsection 4.2). Next we compare the obtained number counts with previous studies (subsection 4.3) and estimate the contribution of the ASAGAO sources to the 1.2 mm EBL (subsection 4.4).

4.1 Completeness and flux boosting

We calculate the completeness, which is the rate at which a source is expected to be detected in a map, to see the effect of noise fluctuations on the source detection. The calculation is conducted on the signal map (corrected for primary beam attenuation). An artificial source of an elliptical Gaussian with the synthesized beam size is injected into a position randomly selected in the map. In order to take into account the effect of source size, the input source is convolved with another Gaussian function. Franco et al. (2018) computed the completeness with different convolving Gaussian FWHM between $0''.2$ and $0''.9$, and found that the completeness is lower for a larger FWHM. Recent ALMA measurements of source size of SMGs ($S_{1\text{ mm}} > 1\text{ mJy}$) show that source sizes (FWHM) range from $0''.08$ to $0''.8$ (e.g., Ikarashi et al. 2015, 2017; Simpson et al. 2015a; Hodge et al. 2016; Umehata et al. 2017). The median source sizes in these studies are $0''.20^{+0''.03}_{-0''.05}$ (Ikarashi et al. 2015), $0''.30 \pm 0''.04$ (Simpson et al. 2015a), and $0''.31 \pm 0''.03$ (Ikarashi et al. 2017). Fujimoto et al. (2017) find a positive correlation between the effective radius in the rest-frame FIR wavelength and FIR luminosity by using a sample of 1034 ALMA sources, suggesting that the ASAGAO sources with fainter flux densities ($S_{1\text{ mm}} \lesssim 1\text{ mJy}$) may have smaller source sizes. This is proved to be valid for the ASAGAO sources based on uv -visibility stacking analysis (Fujimoto et al. 2018).

In the completeness calculation, we take a convolving beam size to be uniformly distributed from $0''.01$ – $0''.5$. We input 30000 artificial sources into the signal map one at a time, each with an integrated flux density randomly selected from 0.05 – 2 mJy by considering the flux range of detected sources. The input sources are then extracted in the same manner as in subsection 3.1. When the input source is detected with a peak $S/N \geq 4.5$, the source is considered to be recovered. The completeness calculation is conducted separately for the central deeper region (coverage >0.6) and the rest (coverage <0.6) to see the effect of the survey depth. The result is shown in figure 13. The completeness calculated in regions with different coverage are consistent within errors and we do not find a significant difference. The completeness is 60% at $S/N = 4.5$, and 100% at $S/N \gtrsim 7$.

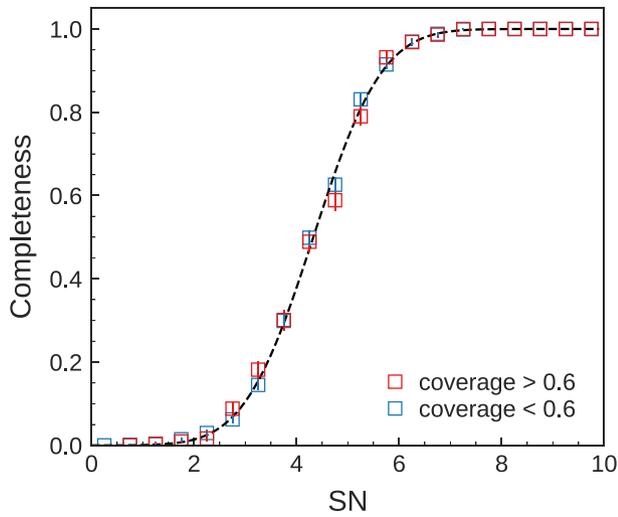


Fig. 13. Completeness calculated for the regions with coverage >0.6 (red) and <0.6 (blue) as a function of input peak S/N . The squares and error bars represent mean and 1σ from the binomial distribution within a bin obtained by 30000 trials in each coverage region. The dashed curve shows the best-fit function of $f(S/N) = \{1 + \text{erf}[(S/N - a)/b]\}/2$ for the entire region, where $(a, b) = (4.33, 1.50)$. (Color online)

When dealing with low- S/N sources, we need to consider the effect that flux densities are boosted by noise (Murdoch et al. 1973; Hogg & Turner 1998). In the course of the completeness simulation, we calculate the ratio between input and output integrated flux densities to estimate the intrinsic flux density of the detected sources (figure 14, top panel). The effect of flux boosting for the sources with $S/N \geq 4.5$ is, on average, less than 15%, and the deboosted flux densities range from $135 \mu\text{Jy}$ to 1.97 mJy . As in the completeness calculation, we do not see any significant difference in the flux boosting between the different coverage regions. The ratio of output peak S/N to input peak S/N is also calculated and shown in figure 14 (bottom panel).

4.2 1.2 mm number counts

Using the 4.5σ sources, we create differential and cumulative number counts. To create number counts, we correct for the contamination of spurious sources, the effective area, and the completeness as follows:

$$\frac{dN}{dS} = \frac{1}{\Delta S} \sum_i \frac{1 - f_{\text{neg}}[(S/N)_i]}{A(S_i)C[(S/N)_i]}, \quad (2)$$

where S_i is the observed source flux density, f_{neg} is the negative fraction accounting for spurious detections, A is the effective area, C is the completeness, and ΔS is the width of the flux bin. Figure 15 shows the differential fraction of the number of negative peaks to positive peaks (f_{neg}) as a function of S/N . The contamination of spurious sources to

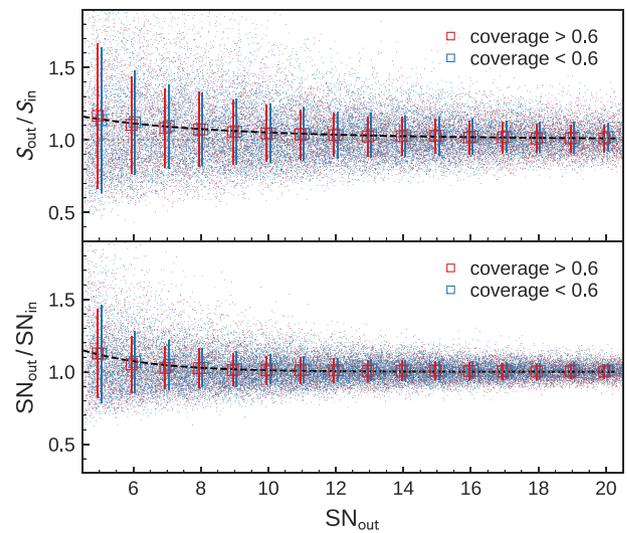


Fig. 14. The ratio between input flux (S_{in}) and output flux (S_{out}) (top) and the ratio between input peak S/N (S/N_{in}) and output peak S/N (S/N_{out}) (bottom) as a function of output peak S/N calculated for the regions with coverage >0.6 (red) and <0.6 (blue). The 30000 trials in each coverage region are presented as dots. The squares and error bars represent mean and 1σ within a bin. The dashed curves show the best-fit function of $f(S/N) = 1 + \exp[a(S/N)^b]$ for the entire region, where $(a, b) = (-0.725, 0.612)$ and $(-0.360, 1.11)$ for the top and bottom panels, respectively. (Color online)

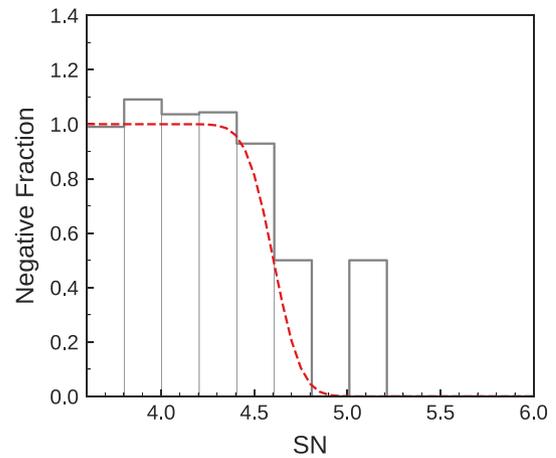


Fig. 15. Differential fraction of negative peaks to positive peaks as a function of peak S/N . The dashed curve represents the best-fit function of $f(S/N) = \{1 + \text{erf}[(S/N - a)/b]\}/2$, where $(a, b) = (4.60, 0.165)$. (Color online)

each source is estimated by using the best-fit function of the negative fraction and is subtracted from unity. Then the counts are divided by the completeness by using the best-fit function as a function of S/N (figure 13). Here we use S/N s corrected for the boosting effect presented in figure 14 (bottom panel). The effective area estimated for each flux density is used as the survey area for a source. The effect of flux boosting on the source flux density is corrected by using the best-fit function shown in figure 14 (top panel). The uncertainties from Poisson fluctuations is estimated from

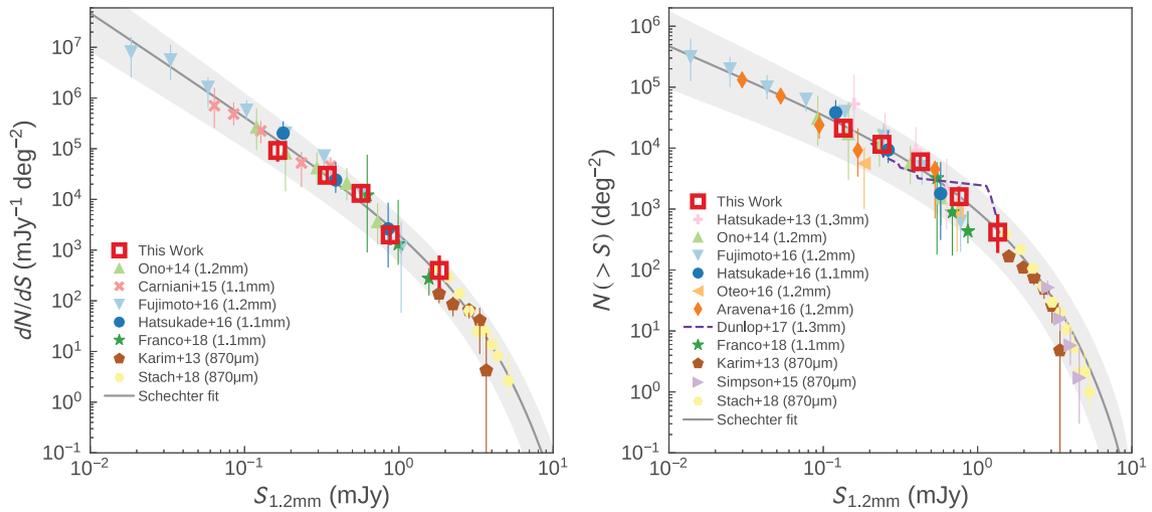


Fig. 16. Differential (left) and cumulative (right) number counts at 1.2 mm obtained for ASAGAO sources (red squares). For comparison, we plot the results for the ALMA blank field surveys of SXDF-ALMA at 1.1 mm (Hatsukade et al. 2016), ASPECS at 1.2 mm (Aravena et al. 2016), HUDF at 1.3 mm (Dunlop et al. 2017), and GOODS-ALMA at 1.1 mm (Franco et al. 2018). Number counts derived from serendipitously detected ALMA sources by Hatsukade et al. (2013), Ono et al. (2014), Carniani et al. (2015), Fujimoto et al. (2016), and Oteo et al. (2016) are also presented. For the bright end, ALMA 870 μm follow-up observations of single-dish sources by Karim et al. (2013), Simpson et al. (2015b), and Stach et al. (2018) are presented. The solid curve and shaded area represent the best-fitting functions in the form of a Schechter function and 1σ error fitted to the differential number counts. The flux densities of the counts are scaled to the wavelength of ASAGAO by assuming a modified black body with a dust emissivity index of $\beta = 1.5$, dust temperature of 35 K, and $z = 2$. (Color online)

Poisson confidence limits of 84.13% (Gehrels 1986), which correspond to 1σ for Gaussian statistics that can be applied to small-number statistics. The derived number counts are shown in figure 16 and table 4.

The differential number counts obtained in this study and previous studies are fitted to a Schechter function of the form

$$\frac{dN}{dS} = \frac{N'}{S'} \left(\frac{S}{S'}\right)^\alpha \exp\left(-\frac{S}{S'}\right). \quad (3)$$

In this fit, we use the ALMA number counts plotted in figure 16, which are based on blank-field surveys and serendipitously detected sources at 1.1–1.3 mm, to constrain the faint flux range (<1 mJy), and the results of 870 μm follow-up observations of single-dish sources (Karim et al. 2013; Stach et al. 2018) for the bright end by scaling the flux densities from 870 μm to 1.2 mm. Here we assume a modified black body with a dust emissivity index of $\beta = 1.5$, dust temperature of 35 K, and $z = 2$. The best-fit parameters are summarized in table 5.

4.3 Comparison with previous ALMA studies

We compare the ASAGAO number counts with the previous results in the ALMA blank-field surveys. The number counts of SXDF-ALMA are obtained by using 23 (4σ) sources detected in a 2 arcmin² area at 1.1 mm (Hatsukade et al. 2016). The ASPECS number counts are derived from

Table 4. Differential and cumulative number counts.*

S (mJy)	N	dN/dS ($10^2 \text{ mJy}^{-1} \text{ deg}^{-2}$)	S (mJy)	N	$N(>S)$ (10^2 deg^{-2})
(1)	(2)	(3)	(4)	(5)	(6)
0.180	6	924^{+552}_{-366}	0.135	45	213^{+64}_{-43}
0.341	12	299^{+114}_{-85}	0.240	39	116^{+26}_{-20}
0.568	17	132^{+40}_{-32}	0.427	27	60^{+15}_{-12}
0.878	7	$20.0^{+10.7}_{-7.4}$	0.759	10	$16^{+7.5}_{-4.9}$
1.828	3	$4.0^{+3.9}_{-2.2}$	1.350	3	$4.2^{+4.1}_{-2.3}$

* (1) Weighted-mean flux density for bin center. (2) Number of sources for differential number counts. (3) Differential number counts. (4) Flux density for bin minimum. (5) Number of sources for cumulative number counts. (6) Cumulative number counts.

Table 5. Best-fit parameters of parametric fit to differential number counts.*

N' (10^2 deg^{-2})	S' (mJy)	α
31.3 ± 16.6	1.34 ± 0.30	-2.03 ± 0.16

*The errors are 1σ .

16 (3σ) sources detected in a deeper 1 arcmin² survey at 1.2 mm, covering a fainter flux range (Aravena et al. 2016). The HUDF number counts are obtained in a 4.5 arcmin² survey at 1.3 mm (Dunlop et al. 2017) by using 16 sources (3.5σ , $S_{1.3 \text{ mm}} > 120 \mu\text{Jy}$) with secure galaxy counterparts.

The GOODS-ALMA number counts are obtained from 20 sources (4.8σ) detected in a 69 arcmin^2 survey at 1.1 mm (Franco et al. 2018). The ASAGAO number counts are constructed from the largest sample among the blank-field surveys, leading to the small uncertainty from Poisson statistics. The flux range connects the fainter range probed by ALMA deep observations and the brighter range constrained by ALMA follow-up observations of single-dish detected sources. We find that our number counts are consistent with those of the previous ALMA blank-field surveys. The number counts obtained by using the ensemble of serendipitously detected sources are also compared (Hatsukade et al. 2013; Ono et al. 2014; Carniani et al. 2015; Fujimoto et al. 2016; Oteo et al. 2016). While the faintest bin of Oteo et al. (2016) is lower than the ASAGAO number counts, these number counts are overall consistent within errors. Note that the lower S/N thresholds ($\lesssim 4.5\sigma$ – 5σ) adopted in previous studies might include a larger fraction of spurious sources and overestimate the number counts, although the number counts are corrected for the contamination of spurious sources (e.g., Oteo et al. 2016; Hatsukade et al. 2016; Umehata et al. 2017, 2018).

4.4 Contribution to extragalactic background light

Using the derived differential number counts, we calculate the fraction of the EBL resolved into discrete sources in this survey. The integration of the ASAGAO differential number counts yields $7.7^{+1.7}_{-1.2} \text{ Jy deg}^{-2}$ ($S_{1.2 \text{ mm}} > 135 \mu\text{Jy}$). The EBL at 1.2 mm (243 GHz) is estimated from the measurements by the Planck satellite (Planck Collaboration 2014) following Aravena et al. (2016) and Muñoz Arancibia et al. (2017). By interpolating the measurements at 217 and 353 GHz, the EBL at 1.2 mm is calculated to be $15.1 \pm 0.59 \text{ Jy deg}^{-2}$. We find that $52^{+11}_{-8}\%$ of the EBL at 1.2 mm is resolved into discrete sources in the ASAGAO map. The integration of the best-fitting function in the form of a Schechter function reaches 100% at $S_{1.2 \text{ mm}} \sim 20 \mu\text{Jy}$, although we note that there is a large uncertainty to extend the function to the faint flux regime. The flux density of $\sim 20 \mu\text{Jy}$ is comparable to the stacked ALMA 1.3 mm signal ($S_{1.3 \text{ mm}} = 20.1 \pm 4.6 \mu\text{Jy}$, corresponding to an SFR of $6.0 \pm 1.4 M_{\odot} \text{ yr}^{-1}$) derived by Dunlop et al. (2017) on the positions of 89 galaxies in the redshift range of $1 < z < 3$ and stellar mass range of $9.3 < \log(M_*/M_{\odot}) < 10.3$. This flux density is also comparable to the stacked flux density of 21 near-infrared (NIR) sources with 3.6 μm magnitudes of $m_{3.6 \mu\text{m}} = 22\text{--}23$ ($S_{1.1 \text{ mm}} = 29 \pm 15 \mu\text{Jy}$, corresponding to an SFR of several $M_{\odot} \text{ yr}^{-1}$) in SXDF-ALMA derived by Wang et al. (2016), who found that $\sim 80\%$ of the EBL is recovered by $m_{3.6 \mu\text{m}} < 23$ sources.

To individually detect these faint submm sources, which significantly contribute to the EBL, it is essential to conduct much deeper observations than in existing deep surveys, or use gravitational lensing effects. Fujimoto et al. (2016) showed that nearly 100% of the EBL can be explained by including gravitational lensed sources at the faint end ($S_{1.2 \text{ mm}} \sim 20 \mu\text{Jy}$). On the other hand, Muñoz Arancibia et al. (2017) argue that their 1σ upper limits to differential counts derived from three galaxy clusters as part of the ALMA Frontier Fields Survey are lower than those of Fujimoto et al. (2016) by ≈ 1 dex and the resolved fraction is only 43% down to $S_{1.1 \text{ mm}} = 13 \mu\text{Jy}$. Since the faintest end of number counts derived from lensed sources depends on the lensing model, deeper surveys in blank fields are essential to resolving this discrepancy.

5 Luminosity function

While IR luminosity functions of submm sources have been extensively studied by Herschel at wavelengths $\leq 500 \mu\text{m}$ (e.g., Gruppioni et al. 2013; Magnelli et al. 2013), the results are affected by source blending and the sensitivity limit due to the large beam size. Studies at 850 μm –1 mm wavelengths have been very limited (Koprowski et al. 2017). In this section we present the methods of constructing IR LFs from the ASAGAO sources (subsection 5.1), and compare the results with previous studies (subsection 5.2). We estimate the contribution of the ASAGAO sources to the cosmic SFR density ($SFRD$) at $z \sim 2$ by using the derived LFs (subsection 5.3).

5.1 IR luminosity function of ASAGAO sources

To estimate LFs, the redshifts of the ASAGAO sources are required. We utilize spectroscopic or photometric redshifts of optical/NIR counterparts. We identify K_s -band selected sources from the catalog of the FourStar galaxy evolution survey (ZFOURGE: Straatman et al. 2016). ZFOURGE covers a total of 400 arcmin^2 , including the ASAGAO region, with a limiting 5σ depth in K_s of 26.0 and 26.3 AB mag for 80% and 50% completeness with masking, respectively. The counterpart identification and SED fitting are described in detail in Yamaguchi et al. (2018), and here we just give a brief explanation. The ASAGAO sources are cross-matched with the ZFOURGE catalog. For point-like K_s -band sources we adopt a search radius of $0''.5$, which is small enough to identify a counterpart. For extended K_s -band sources we adopt a larger radius, up to half-light radius. By using ancillary multi-wavelength data (0.4–500 μm) and our ALMA photometry, SED fitting with the MAGPHYS model (da Cunha et al. 2008, 2015) is performed. The SED templates of Bruzual and

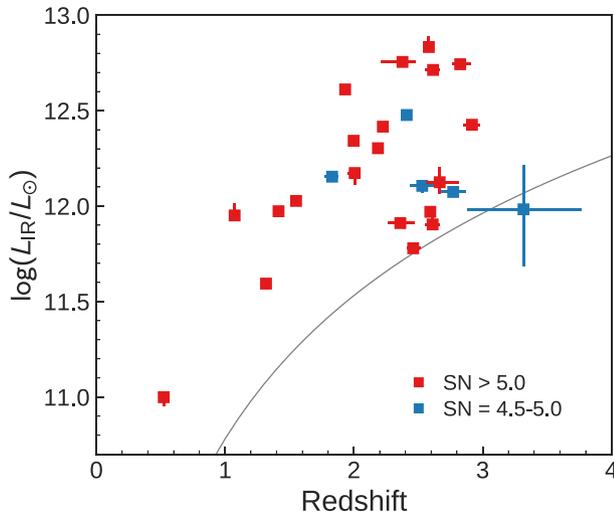


Fig. 17. IR luminosity of the ASAGAO sources with K_s -band counterpart as a function of redshift. The solid curve represents the luminosity limit in this study estimated from the average SED of the 4.5σ sources and a detection limit of $\sigma_{1.2\text{mm}} = 26\ \mu\text{Jy beam}^{-1}$. (Color online)

Charlot (2003) and the dust extinction model of Charlot and Fall (2000) are adopted. The number of ASAGAO sources with ZFOURGE counterparts are 20 (80%) and 25 (56%) for 5σ and 4.5σ sources, respectively. We use the 5σ sources for constructing IR LFs by considering the completeness of the counterpart identification. Note that the 5σ sources without counterparts are likely to be at higher redshifts ($z \gtrsim 4$ –5) based on their optical-ratio SEDs (Yamaguchi et al. 2018), and therefore they do not affect the following discussion for the LFs at $z = 1$ –3 significantly. The spectroscopic or photometric redshift is available in the ZFOURGE catalog. IR luminosities (measured in the rest-frame 8–1000 μm) are derived in the SED fitting. The IR luminosities as a function of redshift are shown in figure 17.

To construct the LFs, we adopt the V_{max} method (Schmidt 1968). This method uses the maximum observable volume of each source. The LF gives the number of ALMA sources in a comoving volume per logarithm of luminosity and is obtained as

$$\Phi(L, z) = \frac{1}{\Delta L} \sum_i \frac{1}{C[(S/N)_i] V_{\text{max},i}}, \quad (4)$$

where $V_{\text{max},i}$ is the maximum observable volume of the i th source, C is the completeness, and ΔL is the width of the luminosity bin. We adopt a luminosity bin width of $\Delta \log(L) = 0.6$. Because the noise level in the map is not uniform, we need to take into account the effective solid angle where a source can be detected for calculating V_{max} . Following the description of Novak et al. (2017), where they construct radio LFs taking into account a nonuniform noise in their radio maps, we calculate V_{max} as the integration of

Table 6. IR luminosity functions.

$\log(L_{\text{IR}}/L_{\odot})^*$	N	$\log(\Phi/\text{Mpc}^{-3} \text{ dex}^{-1})$
	1.0 < z < 2.0	
11.86	4	$-3.89^{+0.25}_{-0.28}$
12.46	2	$-4.34^{+0.37}_{-0.45}$
	1.5 < z < 2.5	
11.91	6	$-3.66^{+0.20}_{-0.22}$
12.44	3	$-4.25^{+0.30}_{-0.34}$
	2.0 < z < 3.0	
11.94	7	$-3.05^{+0.19}_{-0.20}$
12.57	6	$-3.97^{+0.20}_{-0.22}$

*Weighted-mean luminosity in each bin.

comoving volume spherical shells as

$$V_{\text{max},i} = \int_{z_{\text{min}}}^{z_{\text{max}}} \frac{\Omega[S_i(z)]}{4\pi} \frac{dV}{dz}, \quad (5)$$

where z_{min} and z_{max} are the maximum and minimum redshifts of a redshift bin, $S_i(z)$ is the flux density of source i observed when it is located at z , and Ω is the solid angle where source i with a flux density of $S_i(z)$ can be detected with $S/N > 5$. $S_i(z)$ is estimated from the SED model of each source, and $\Omega[S_i(z)]$ is derived from the effective area for $S_i(z)$. Because the number of sources in each bin is small, the error of the LFs is estimated from Poisson confidence limits of 84.13% (corresponding to Gaussian 1σ errors) in Gehrels (1986). We derive IR LFs in the redshift ranges of $1.0 < z < 2.0$, $1.5 < z < 2.5$, and $2.0 < z < 3.0$ by using 6 (mean redshift of $z_{\text{mean}} = 1.55$), 9 ($z_{\text{mean}} = 2.12$), and 13 ($z_{\text{mean}} = 2.49$) sources, respectively. To increase the number of sources in each redshift bin we adopt a bin width of 1.0, resulting in overlap of the bins. The derived IR LFs are presented in table 6 and figure 18. Our study constrains the faintest luminosity end of the LF at $2.0 < z < 3.0$ among other studies.

5.2 Comparison with previous studies

We compare the ASAGAO LFs with those derived from sources detected with ALMA, SCUBA2, and Herschel. Koprowski et al. (2017) derived rest-frame 250 μm LFs and IR LFs up to $z \sim 5$ by using 16 1.3 mm sources detected in the ALMA HUDF survey (Dunlop et al. 2017) for constraining the faint end and 577 850 μm sources detected in the COSMOS and UDS fields as part of the SCUBA-2 Cosmology Legacy Survey (S2CLS: Chen et al. 2016; Geach et al. 2017; Michałowski et al. 2017) for constraining the bright end. The wide coverage of the luminosity range and the large sample for the bright end allowed them to examine the evolution of LFs derived for submm sources.

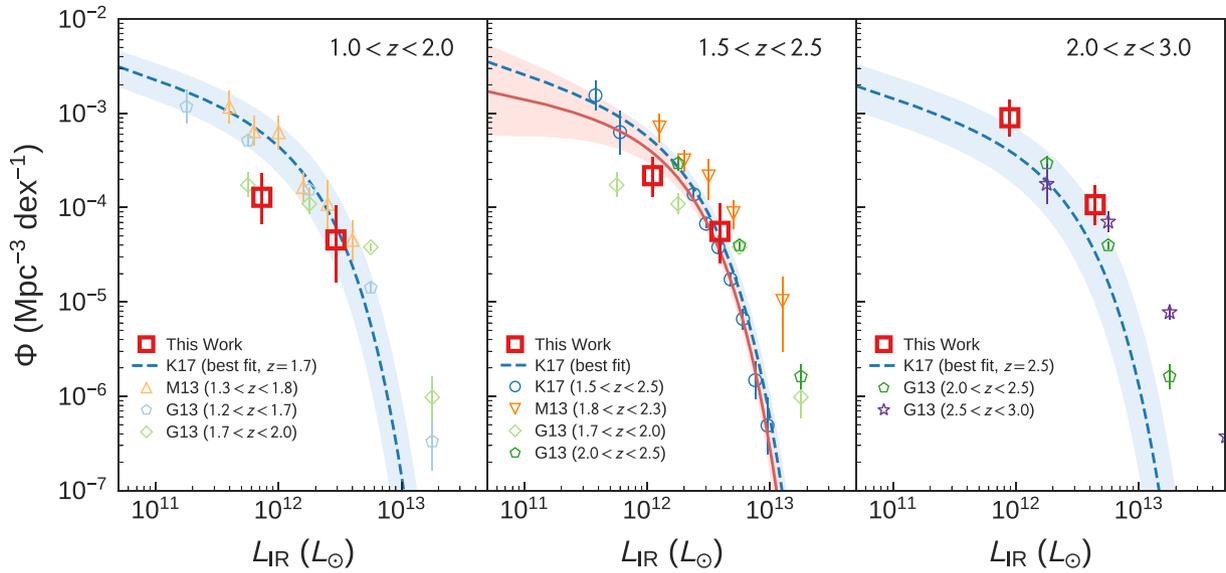


Fig. 18. IR luminosity functions constructed from the ASAGAO sources at $1.0 < z < 2.0$ (left), $1.5 < z < 2.5$ (middle), and $2.0 < z < 3.0$ (right). We plot luminosity functions obtained in Koprowski et al. (2017) (K17) by using 1.3 mm sources from the ALMA HUDF survey and 850 μm sources from the SCUBA-2 Cosmology Legacy Survey. The dashed curve and shaded area represent the best-fitting functions and 1σ error of Koprowski et al. (2017). At $1.5 < z < 2.5$, we plot their data points derived from the V_{max} method and the best-fitting function. At $1.0 < z < 2.0$ and $2.0 < z < 3.0$, we plot their functional form of the redshift evolution of the LF derived from the maximum-likelihood method, adopting the mean redshifts of the ASAGAO sources in each redshift bin ($z = 1.55$ and $z = 2.49$, respectively). The results of Herschel observations by Magnelli et al. (2013) (M13) and Gruppioni et al. (2013) (G13) are also compared. The solid curve and shaded area represent the the best-fitting Schechter function and 1σ error fitted to the results of ASAGAO and Koprowski et al. (2017) at $1.5 < z < 2.5$. (Color online)

They derived LFs for four redshift bins, $z = 0.5\text{--}1.5$, $1.5\text{--}2.5$, $2.5\text{--}3.5$, and $3.5\text{--}4.5$, by using the V_{max} method. They determined the faint-end slope of $\alpha = -0.4$ in the Schechter form of

$$\Phi(L) = \Phi_* \left(\frac{L}{L_*} \right)^\alpha \exp\left(\frac{-L}{L_*} \right), \quad (6)$$

fitting to the data in the redshift bin of $1.5 < z < 2.5$, where ALMA sources are available for constraining the faint end. The remaining Schechter-function parameters were determined by fixing the faint-end slope α to -0.4 . To estimate the continuous form of the redshift evolution of the LF, they used the maximum-likelihood method. In figure 18, we plot their data points and the best-fitting function determined in the redshift bin of $1.5 < z < 2.5$, and the LFs determined from the maximum-likelihood method for the redshift bins of $1.0 < z < 2.0$ and $2.0 < z < 3.0$. They find that the LFs are well characterized by the number density/luminosity evolution of LFs with positive luminosity evolution coupled with negative density evolution with increasing redshift. We find that the ASAGAO LFs are consistent with those of Koprowski et al. (2017) within the errors, supporting the evolution of LFs derived in Koprowski et al. (2017), although the large uncertainties of our LFs due to the small sample size and the limited coverage of IR luminosity do not allow us to further discuss the density/luminosity evolution of submm sources. The ASAGAO LFs at $2.0 < z < 3.0$ are

above their results, while those results are consistent. This may suggest a stronger luminosity evolution or weaker density evolution. The fainter bin of the ASAGAO LFs at $1.0 < z < 2.0$ is a factor of a few lower than that of Koprowski et al. (2017). This may be due to the fact that they fixed the faint-end slope when deriving the LF evolution.

The results of Herschel observations are also compared in figure 18. Gruppioni et al. (2013) derived IR LFs up to $z \sim 4$ by using the data from the Herschel-PEP survey in combination with the Herschel-HerMES data. Magnelli et al. (2013) presented IR LFs up to $z \sim 2$ obtained in the GOODS fields from the PEP and the GOODS-Herschel programs. Koprowski et al. (2017) found a discrepancy between the results based on submm sources and Herschel sources at the bright end, and concluded that Herschel results are contaminated and biased high by a mix of source blending and misidentification of counterparts (and hence redshift) due to the large beam size of Herschel/SPIRE. Although the Herschel results are scattered and the redshift ranges are not exactly the same as in ours, we find that they are overall consistent with the ASAGAO LFs.

We fit the IR LFs at $1.5 < z < 2.5$ obtained from the ASAGAO sources and the results of Koprowski et al. (2017) with a Schechter function of the form of equation (6). The best-fitting parameters are presented in table 7. The derived spectral slope of $\alpha = -0.22 \pm 0.28$ is flatter than $\alpha =$

Table 7. Best-fit parameters of parametric fit to LF at $1.5 < z < 2.5$ by using the ASAGAO sources and the results of Koprowski et al. (2017).*

$\log(\Phi_*/\text{Mpc}^{-3} \text{ dex}^{-1})$	$\log(L_*/L_\odot)$	α
-3.07 ± 0.07	12.12 ± 0.05	-0.22 ± 0.28

*The errors are 1σ .

-0.4 as derived by Koprowski et al. (2017), but consistent within the errors. In order to constrain the redshift evolution of LFs, it is essential to conduct wider-area surveys for obtaining a larger sample in a wide range of IR luminosity.

5.3 Contribution to the cosmic *SFR* density

Integrating the best-fit IR LF and converting it to *SFRD*, we estimate the contribution of ASAGAO sources to the cosmic *SFRD* at $z \sim 2$. *SFR* is converted from IR luminosity by using the relation of Kennicutt (1998) and corrected to a Chabrier (2003) IMF. The integration of the best-fitting luminosity function down to the lowest luminosity of the sources [$\log(L_{\text{IR}}/L_\odot) = 11.78$] gives an *SFRD* of $7.2_{-1.9}^{+3.0} \times 10^{-2} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. This is consistent with the results of Yamaguchi et al. (2018), where they derived the *SFRD* by counting the contribution from individual ASAGAO sources. We compare the *SFRD* with the total *SFRD* (UV + IR) at $z \sim 2$ estimated in previous studies: $0.13 M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 2$ by Madau and Dickinson (2014), or $0.11\text{--}0.12 M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$ at $z = 1.8\text{--}2.25$ by Burgarella et al. (2013). The fraction of *SFRD* contributed by the ASAGAO sources is $\approx 60\%\text{--}90\%$ at $z \sim 2$, indicating that the major portion of *SFRD* at that redshift is composed of obscured star formation from sources with $\log(L_{\text{IR}}/L_\odot) \gtrsim 11.8$ (e.g., Dunlop et al. 2017; Koprowski et al. 2017). This is reasonable considering that the IR luminosity is somewhat lower than the turnover IR luminosity of the best-fit Schechter function.

6 Conclusions

We performed the ALMA twenty-six arcmin² survey of GOODS-S at one millimeter (ASAGAO). The central 26 arcmin² area of the GOODS-S field was observed at 1.2 mm, providing a map with $1\sigma \sim 61 \mu\text{Jy beam}^{-1}$ (250 k λ -taper) and a synthesized beam size of $0''.51 \times 0''.45$. Combining our survey with the ALMA archival data available in the GOODS-S field (HUDF by Dunlop et al. 2017; GOODS-ALMA by Franco et al. 2018), we obtained a deeper map for the 26 arcmin² area, which has an rms noise level of $1\sigma \sim 30 \mu\text{Jy beam}^{-1}$ for the central region with a 250 k λ taper and a synthesized beam size of $0''.59$

$\times 0''.53$. We find 25 sources at 5σ and 45 sources at 4.5σ in the combined ASAGAO map, providing the largest source catalog among ALMA blank field surveys. The flux densities are consistent with those estimated in the other ALMA GOODS-S surveys by considering the difference in observing wavelength.

The larger sample allows us to construct 1.2 mm number counts with smaller uncertainties from Poisson statistics. The flux coverage of the number counts connects the fainter range probed by ALMA deep observations and the brighter range constrained by ALMA follow-up observations of single-dish-detected sources. We find that our number counts are consistent with previous ALMA studies. Integrating the derived differential number counts, we find that $52_{-8}^{+11}\%$ of the EBL at 1.2 mm is resolved into the discrete sources. The integration of the best-fitting function reaches 100% at $S_{1.2\text{mm}} \sim 20 \mu\text{Jy}$, although there is a large uncertainty to extend the function to the fainter flux range. Deeper surveys are required to individually detect faint submm sources, which significantly contribute to the EBL.

Using the 5σ sources, we construct IR LFs in the redshift ranges of $1.0 < z < 2.0$, $1.5 < z < 2.5$, and $2.0 < z < 3.0$. Our study constrains the faintest luminosity end of the LF at $2.0 < z < 3.0$ among other studies. We find that the ASAGAO LFs are consistent with those of Koprowski et al. (2017), supporting the evolution of LFs (positive luminosity evolution and negative density evolution with increasing redshift) derived in Koprowski et al. (2017). The integration of the best-fitting LF down to the lowest luminosity of the sources [$\log(L_{\text{IR}}/L_\odot) = 11.78$] gives an *SFRD* of $7.2_{-1.9}^{+3.0} \times 10^{-2} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. We find that the IR-based star formation of ASAGAO sources contributes to $\approx 60\%\text{--}90\%$ of the *SFRD* at $z \sim 2$ derived from UV-IR observation, indicating that the major portion of $z \sim 2$ *SFRD* is composed of sources with $\log(L_{\text{IR}}/L_\odot) \gtrsim 11.8$.

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