Blind Millimeter Line Emitter Search using ALMA Data Toward Gravitational Lensing Clusters

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Abstract

We present the results of a blind millimeter line emitter search using ALMA Band 6 data with a single-frequency tuning toward four gravitational lensing clusters (RXJ1347.5–1145, Abell S0592, MACS J0416.1–2403, and Abell 2744). We construct 3D signal-to-noise ratio (S/N) cubes with 60 and 100 MHz binning, and search for millimeter line emitters. We do not detect any line emitters with a peak S/N > 5, although we do find a line emitter candidate with a peak S/N ≳ 4.5. These results provide upper limits to the CO and [C II] luminosity functions at z ≲ 0.3, 0.7, 1.2, and 6, respectively. Because of the magnification effect of gravitational lensing clusters, the new data provide the first constraints on the CO and [C II] luminosity functions at unprecedentedly low luminosity levels, i.e., down to L_{CO} < 10^{9}–10^{10} K km s^{-1} pc^{-2} and L_{[C II]} < 10^{8}–10^{10} L_{\odot}, respectively. Although the constraints to date are not yet stringent, we find that the evolution of the CO and [C II] luminosity functions are broadly consistent with the predictions of semi-analytical models. This study demonstrates that the wide observations with a single-frequency tuning toward gravitational lensing clusters are promising for constraining the CO and [C II] luminosity functions.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: ISM – surveys

1. Introduction

Recent studies have unveiled the cosmic star formation history based on multi-wavelength observations (e.g., Madau & Dickinson 2014; Bouwens et al. 2015, and reference therein). The cosmic star formation rate density (SFRD) has a peak level between z ∼ 3 and z ∼ 1, and it subsequently decreases rapidly toward z = 0. However, the role of dust-obscured star formation at high redshifts (especially at z > 3–4) and the physical cause governing the cosmic star formation history are still uncertain.

One of the promising ways to resolve these questions is to observe (sub-)millimeter emission lines. The [C II] 158 μm line is expected to be a tracer of dust-obscured star formation in local to distant galaxies (e.g., De Leeze et al. 2011, 2014; Smail et al. 2011; Sargsyan et al. 2012, 2014). The molecular gas content of galaxies can be observed via CO rotational transition lines (e.g., Solomon et al. 1987; Tacconi et al. 2013). The molecular gas mass of galaxies is one of the fundamental properties for understanding the cause of cosmic star formation history because the molecular phase of the interstellar medium is considered to be the fuel for star formation activities. However, observations of (sub-)millimeter emission lines have been limited to follow-up studies of galaxies, which are preselected by optical, near-infrared (NIR), or (sub-)millimeter wavelengths (e.g., Daddi et al. 2010; Tacconi et al. 2010; Carilli & Walter 2013; Tacconi et al. 2013; Genzel et al. 2015; Tacconi et al. 2017, and references therein). In these cases, the selection is based on the star formation properties or stellar mass of a given galaxy. Accordingly, these samples are biased.

Based on the above reasons, constraining the luminosity functions of (sub-)millimeter line emitters via unbiased (sub-)millimeter line emitter surveys is necessary in order to unveil the cosmic star formation history. For example, the “line intensity mapping” technique is a useful way to constrain luminosity functions (e.g., Keating et al. 2016). So far, individual properties of line emitters have remained unexplored because the emission from a multitude of galaxies over a wide range of line luminosities are integrated in this “line intensity mapping” technique.

The development of observational instruments such as the IRAM Plateau de Bure Interferometer, or NOEMA, and the
Atacama Large Millimeter/submillimeter Array (ALMA) has made unbiased (sub-)millimeter line emitter searches feasible (e.g., Decarli et al. 2014, 2016; Walter et al. 2014, 2016; Aravena et al. 2016). However, such line emitter searches based on spectroscopic scan observations (i.e., observed frequency range > several tens of gigahertz) can often be expensive in terms of total observing time. Therefore, serendipitous detections of line emitters (e.g., Tamura et al. 2014; Hayatsu et al. 2017; Umehata et al. 2017) and line emitter searches using archival data (e.g., Matsuda et al. 2015; Miller et al. 2016) based on high-sensitivity observations of ALMA have been reported.

In this paper, we present the results of a blind millimeter line emitter search using ALMA Band 6 data with only a single-frequency tuning (i.e., observed frequency range ≃ 8 GHz) toward four gravitational lensing clusters, RXJ1347.5−1145, Abell S0592, MACS J0416.1−2403, Abell 2744; images of these gravitational lensing clusters obtained by the Hubble Space Telescope are displayed in Figure 1. From our search, we constrain the CO luminosity functions at $z \lesssim 1$ and the [C II] luminosity function at $z \approx 6$.

According to the predictions of semi-analytical models (e.g., Obreschkow et al. 2009a, 2009b; Lagos et al. 2012; Popping et al. 2016), the number density of CO line emitters (i.e., CO luminosity function) evolve significantly at $z \lesssim 1$, which is in marked contrast to the weak evolution at $z = 1–4$ (Popping et al. 2016). Because of the magnification effect of gravitational lensing clusters, we can constrain the fainter end of the CO luminosity function, which is difficult to observe in previous unlensed blank field observations. Constraining the faint end of CO luminosity functions ($L'_\text{CO} \lesssim 10^9$ K km s$^{-1}$ pc$^2$) is particularly important because it is dominated by non-starburst galaxies, which are the main contributors to the cosmic SFRD. The faint end of the CO luminosity functions are also affected by the CO spectral line energy distributions of galaxies, which reflect the density and temperature of the interstellar medium (e.g., Lagos et al. 2012; Popping et al. 2016). Furthermore, the [C II] luminosity function can be a useful tool with which to

![Figure 1. Images of four lensing clusters obtained by HST.](image)
estimate the cosmic SFRD at \( z \approx 6 \), where the contribution from dusty galaxies to the cosmic SFRD is still uncertain.

This paper is structured as follows. Section 2 presents the ALMA data and methods of our line emitter search. In Section 3, we report the results of our line emitter search. Then, we discuss the CO and [C\text{II}] luminosity functions in Section 4. Section 5 presents the summary and conclusion. Throughout this paper, we assume a \( \Lambda \) cold dark matter cosmology with \( \Omega_M = 0.3, \Omega_{\Lambda} = 0.7 \), and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\).

## 2. Data and Methods

### 2.1. ALMA Data

Here, we present the ALMA data. Our ALMA Band 6 continuum observations were carried out as an ALMA Cycle 2 program (Project ID: 2013.1.00724.S, PI: H. Ezawa) on 2015 April 9 and 10 toward two gravitational lensing clusters (RXJ1347.5–1145 and Abell S0592). For the ALMA observation, 35–38 antennas were employed. The minimum and maximum baselines were 15.1 and 348.5 m, respectively. For RXJ1347.5–1145 (for Abell S0592), the phase calibrator was J1337–1257 (J0068–5456), the bandpass calibrators were J1337–1257 and J1256–0547 (J1107–4449 and J1058–0133), and the flux calibrators were Titan and Ganymede (Ganymede). The observed area, observed frequency, frequency setting, achieved continuum sensitivities, and synthesized beam sizes are summarized in Table 1.

We used additional Band 6 continuum observations toward another two gravitational lensing clusters (MACS J0416.1–2403 and Abell 2744) to expand our survey volume. These observations were also carried out as an ALMA Cycle 2 program (Project ID: 2013.1.00999.S, PI: F. Bauer). All data sets are public in the ALMA science archive. In Table 1, we summarize the results of these continuum observations.

From the calibrated measurement sets of clusters, we create 3D data cubes against each spectral window with two different frequency resolutions, i.e., 60 and 100 MHz (corresponding to about 66.7 km s\(^{-1}\) and 111 km s\(^{-1}\) at 270 GHz, respectively). The calibrated visibilities are Fourier transformed using the task CLEAN in the Common Astronomy Software Application (CASA; McMullin et al. 2007). In this study, we use cubes without beam deconvolution employing the CLEAN algorithm (Högborn 1974), i.e., “dirty cubes,” to search for line emitters, because no strong emission above 6\( \sigma \) is found in these cubes (see Figure 2). The achieved angular resolutions of the 3D data cubes are approximately 1\( \text{arcsec} \)×1\( \text{arcsec} \). Note that the frequency resolutions of the original data are about 35 km s\(^{-1}\), 35 km s\(^{-1}\), 18 km s\(^{-1}\), and 18 km s\(^{-1}\) for RXJ1347.5–1145, Abell S0592, MACS J0416.1–2403, and Abell 2744, respectively.

### 2.2. Methods of Line Emitter Search

First, we calculate the standard deviations in each channel and examine 3D signal-to-noise ratio (S/N) cubes by dividing each data cube channel with its standard deviation. Note that we use the data cubes before the correction of the primary beam attenuation pattern to calculate the standard deviations. In Figure 2, we present the S/N distributions of the 3D data cube with 60 MHz binning. Next, we apply CLUMPFIND software (Williams et al. 1994) to the 3D S/N cubes to search for line emitter candidates with a peak S/N > 5. We adopted the following parameters of CLUMPFIND: \( \Delta S = 2\sigma \) and \( S_{\text{start}} = 4\sigma \), where \( \Delta S \) is the contouring interval and \( S_{\text{start}} \) is the starting contour level as discussed in Williams et al. (1994). Finally, we remove spurious detections by eye; specifically, we deem line emitter candidates that were not detected with a S/N > 3 in any channel adjacent to their peak channel as spurious and exclude them.

### 3. Results

We do not detect any significant line emission in our search. The S/N distributions are well fitted by Gaussian functions, which also support non-detections (Figure 2). The typical apparent 1\( \sigma \) noise levels of the data cubes are \( \sigma \approx 1.4, 1.2, 0.73, \) and 0.95 mJy beam\(^{-1}\) with 60 MHz binning and \( \sigma \approx 1.2, 1.0, 0.56, \) and 0.77 mJy beam\(^{-1}\) with 100 MHz binning for RXJ1347.5–1145, Abell S0592, MACS J0416.1–2403, and Abell 2744, respectively (Table 1). Thus, if we assume \( \Delta V = 200 \) km s\(^{-1}\), as presumed in Decarli et al. (2016), the \( 3\sigma \) limiting apparent CO luminosities are estimated to be \( \mu L_{\text{CO}} \approx 5.5 \times 10^8, 1.8 \times 10^9, \) and \( 2.9 \times 10^9 \) K km s\(^{-1}\) pc\(^2\) for CO(3–2) at \( z \approx 0.3, \) CO(4–3) at \( z \approx 0.7, \) and CO(5–4) at \( z \approx 1.2, \) respectively. Note that \( \Delta V \) and \( \mu \) are the velocity-width and the gravitational-lensing magnification factor, respectively. For the [C\text{II}] 158 \( \mu \)m line at \( z \approx 6 \), the \( 3\sigma \) limiting apparent [C\text{II}] luminosities are estimated to be...
\[ \mu L_{\text{[CII]}} \approx 1.0 \times 10^9, 8.5 \times 10^8, 4.7 \times 10^8, \text{and } 6.5 \times 10^8 L_\odot. \]

In the case of the [C II] 158 \, \mu m line, we assume \( \Delta V = 300 \, \text{km} \, \text{s}^{-1} \) as explained in Aravena et al. (2016).

If we adopt a detection threshold of \( S/N = 4.0 \), there is a tentative detection of a line emitter at \((\alpha_{2000}, \delta_{2000}) = (13^{h} 47^{m} 30^{s}, -11^{\circ} 45^{'} 26^{''} 59)\) in RXJ1347.5–1145 (see Figures in Appendix; hereafter RXJ1347-emitter1). RXJ1347-emitter1 is detected with 4.5\( \sigma \) at the peak channel in the 60 MHz binning data cube and detected with 4.3\( \sigma \) at next to the peak channel. RXJ1347-emitter1 is also detected with 5.8\( \sigma \) in the 100 MHz binning data cube, but only detected at the peak channel. RXJ1347-emitter1 has no optical/NIR counterpart (see Figures in Appendix). RXJ1347-emitter1 is not detected in the ALMA continuum map. Therefore, the negative tail of the noise distribution of the 60 MHz binning data cubes also extends to \( S/N = -4.5 \) (see Figure 2) and is only detected at the peak channel in the 100 MHz binning data cube. Thus, we treat RXJ1347-emitter1 as the “line emitter candidate” in this paper. Further details of RXJ1347-emitter1 will be provided in Appendix.

González-López et al. (2017) also search for line emitters using MACS J0416.1–2403 and Abell 2744 data, and report some detections (six in MACS J0416.1–2403 and three in Abell 2744). This discrepancy is simply because our criterion are more conservative than theirs.

4. CO and [C II] Luminosity Functions

We define luminosity bins as ranging from our 3\( \sigma \)-limiting apparent luminosity (see Section 3) to a 0.5 dex higher luminosity. Because of the magnification due to gravitational lensing, we can search for lower line luminosities than the 3\( \sigma \)-limiting apparent line luminosities. Accordingly, we adopt three intrinsic (i.e., demagnified) luminosity bins as displayed in Table 2. Note that for CO(3–2), we define two intrinsic luminosity bins because the survey volume for the lowest intrinsic luminosity bin becomes very small, as explained later in this section.

To constrain the CO and [C II] luminosity functions, it is necessary to estimate the co-moving survey volume. For this purpose, we used gravitational lensing models constructed with the GLAFIC software, which adopt a standard \( \chi^2 \) minimization to determine the best-fit mass model (see Oguri 2010, for details). For MACS J0416.1–2403 and Abell 2744 we use public GLAFIC mass models (version 3.0) that are available at Space Telescope Science Institute (STScI) website\footnote{https://archive.stsci.edu/prepds/frontier/lensmodels/} (Kawamata et al. 2016). For the other two clusters, we use mass models obtained by T. Kitayama et al. 2017, in preparation (for RXJ1347.5–1145) and M. Oguri et al. 2017, in preparation (for Abell S0592). These models are constructed in a similar way to Kawamata et al. (2016).
Table 2
The Constraint on Densities of Line Emitters

| Line       | Redshift Range       | $\log L_{\text{mir}}$ (K km s$^{-1}$ pc$^2$) | $V_{\text{com}}$ (Mpc$^3$) | Density (Mpc$^{-3}$) |
|------------|-----------------------|---------------------------------------------|-----------------------------|-----------------------|
| CO(3–2)   | 0.257–0.276, 0.335–0.357$^a$ | 8.3–8.8 | 0.6778$^{+0.1666}_{-0.2799}$ | $<2.7^{+9.9}_{-0.5}$ |
|           | 0.286–0.271, 0.346–0.361$^b$ | 8.8–9.3 | 285.5$^{+2.6}_{-2.4}$ | $(6.4^{+9.0}_{-8.8}) \times 10^{-3}$ |
| CO(4–3)   | 0.677–0.701, 0.780–0.808$^a$ | 8.3–8.8 | 10.94$^{+1.16}_{-1.09}$ | $(1.7^{+0.5}_{-0.2}) \times 10^{-3}$ |
|           | 0.695–0.714, 0.794–0.815$^b$ | 8.8–9.3 | 316.8$^{+39.5}_{-36.0}$ | $(5.8^{+0.9}_{-0.8}) \times 10^{-3}$ |
|           |                       | 9.3–9.8 | 768.5$^{+11.0}_{-9.9}$ | $(2.4^{+0.4}_{-0.4}) \times 10^{-3}$ |
| CO(5–4)   | 1.10–1.13, 1.22–1.26$^a$ | 8.5–9.0 | 47.42$^{+2.68}_{-2.63}$ | $(3.9^{+0.4}_{-0.3}) \times 10^{-2}$ |
|           | 1.12–1.14, 1.24–1.27$^b$ | 9.0–9.5 | 642.5$^{+58.8}_{-50.4}$ | $(2.9^{+0.3}_{-0.3}) \times 10^{-3}$ |
|           |                       | 9.5–10.0 | 1102$^{+126}_{-96}$ | $(1.7^{+0.2}_{-0.2}) \times 10^{-3}$ |
| [C II] 158 $\mu$m | 5.91–6.01, 6.34–6.45$^a$ | 8.2–8.7$^c$ | 216.0$^{+14.9}_{-9.9}$ | $(8.5^{+1.4}_{-1.2}) \times 10^{-3}$ |
|           | 5.99–6.07, 6.40–6.48$^b$ | 8.7–9.2$^c$ | 1896$^{+178}_{-128}$ | $(9.7^{+1.0}_{-0.9}) \times 10^{-4}$ |
|           |                       | 9.2–9.7$^c$ | 2525$^{+444}_{-331}$ | $(7.3^{+1.1}_{-1.0}) \times 10^{-4}$ |

Notes. (1) Observed line. (2) Observed redshift range. (3) Intrinsic (i.e., demagnified) line luminosities. (4) Co-moving survey volume. (5) The 1$\sigma$ confidence upper limits on the densities of line emitters, which are calculated by using the Poisson statistics by Gehrels (1986).

$^a$ Observed redshift range of RXJ1347.5–1145 and Abell S0592.
$^b$ Observed redshift range of MACS J0416.1–2403 and Abell 2744.
$^c$ For [C II] 158 $\mu$m line, units of line luminosities are $L_{\odot}$.

In Figures 3 and 4, we plot the effective (i.e., real) co-moving survey volume as a function of magnification factors and intrinsic 1$\sigma$ sensitivities, respectively. For CO(3–2), the demagnified survey volume is small, especially in the high magnification area. This is because the CO(3–2) emitters at $z \sim 0.3$ are located in front of the gravitational lensing clusters at $z \lesssim 0.3$ and are thus not affected by gravitational lensing. This means that the non-null contribution at $\mu > 1$ values only comes from Abell S0592.

We use Markov Chain Monte Carlo (MCMC) methods to estimate model uncertainties as with the case of Kawamata et al. (2016). For MACS J0416.1–2403 and Abell 2744, the results of MCMC methods are also available at STScI website1. For MCMC methods we change following parameters: virial parameters, velocity dispersion, truncation radius, dimensionless parameter $\eta$, and redshifts of lensed galaxies (see Kawamata et al. 2016 for details). The resulting MCMC chain typically consists of hundreds of thousands of points. From the MCMC chain we randomly pick 100 parameter sets to estimate the error in our volume estimate from the mass model uncertainty. Specifically, we estimate the co-moving volume for each parameter set, repeat it for the 100 parameter set, and derive the model uncertainties. Here, we define the range between the maximum and minimum co-moving survey volume as the model uncertainty. Our co-moving survey volume of each luminosity bin and the 1$\sigma$ confidence upper limits on the densities of line emitters, which are calculated by using the Poisson statistics by Gehrels (1986), are summarized in Table 2. Note that our estimated errors can be underestimated because we do not include systematic errors between different lens models. For example, the area with a magnification between 5 and 10 in Abell 2744 can change by almost $\sim$20% between different lens models released on the STScI website1 (Wang et al. 2015; Kawamata et al. 2016; Priewe et al. 2017).

Note that the limiting luminosities do not depend on the assumed line profiles. For instance, if we adopt the limiting luminosities following our detection criterion explained in Section 2.2 (i.e., it is detected with 5$\sigma$ flux density in one channel and 3$\sigma$ in a neighboring channel), the results do not change. For example, for CO(4–3), the apparent limiting luminosity is estimated to be $\mu L_{\text{CO}(4–3)} \approx 10^{9.2}$ K km s$^{-1}$ pc$^2$ (in 60 MHz binning cubes), which is comparable with the limiting luminosity presented in Section 3. In this case, the typical magnification factor corresponding to the faintest luminosity bin in the Table 2 (i.e., $L_{\text{CO}(4–3)} \approx 10^{8.5}$ K km s$^{-1}$ pc$^2$) is $\mu \approx 5$. According to Figure 3, the co-moving survey volume corresponding to this case (i.e., $\mu \approx 5$) is estimated to be $V_{\text{com}} \approx 14$ Mpc$^3$, which is comparable with Table 2.

4.1. CO Luminosity Functions

In Figure 5, we show our constraints on the CO luminosity functions (red symbols). In order to avoid CO excitation uncertainties, we do not convert $L_{\text{CO}(3–2)}$, $L_{\text{CO}(4–3)}$, and $L_{\text{CO}(5–4)}$ into $L_{\text{CO}(1–0)}$ in this paper. In gravitational lensing clusters, the effective survey volumes with a large magnification factor are small, as shown in Figures 3 and 4. This is the reason why our constraints on the CO luminosity functions at the faintest intrinsic luminosity bins are not strong. We only plot the best-fitting case in Figure 5, because model uncertainties on luminosity functions are small (see Table 2).

In the same plot (Figure 5) we also show the predictions based on semi-analytical cosmological models by Obreschkow et al. (2009a, 2009b), Lagos et al. (2012), and Popping et al. (2016). As shown in Figure 5, our constraints are consistent with their predictions.

We also plot the latest results of the ALMA SPECTroscopic Survey in the Hubble Ultra-deep Field (ASPECS Decarli et al. 2016; Walter et al. 2016; cyan shaded regions). However, they only use peak values to identify line emitters. To make a fair comparison, we reanalyze their ALMA Band 6 data...
following our procedure, which is explained in Section 2.2. In our procedure, we detect two emission lines, which are detected in ASPECS as 1 mm.1 and 1 mm.2 (Decarli et al. 2016; Walter et al. 2016). According to Decarli et al. (2016), these two lines represent the CO emission from one line emitter at $z = 2.54$. Therefore, we can only place upper limits on the CO luminosity functions at $z \lesssim 1$ (yellow symbols in Figure 5) from the ASPECS data. As shown in Figure 5, our constraints on the CO luminosity functions are consistent with the ASPECS results at similar luminosity ranges ($L'_\mathrm{CO} \sim 10^9 \mathrm{K} \mathrm{km} \mathrm{s}^{-1} \mathrm{pc}^2$). Although the upper limit is about 1–2 orders of magnitude larger than the predictions of semi-analytical models, we can expand the range of luminosity to $\gtrsim 0.5$ dex lower than previous observations, although the current constraints are very coarse.

Based on our upper limits, we constrain the density evolution of the CO luminosity functions between $z = 0$ and $z \simeq 1$. As shown in Figure 5, the evolution of the CO luminosity functions between $z = 0$ and $z \simeq 1$ are consistent with the predictions of semi-analytical models by Obreschkow et al. (2009a, 2009b), Lagos et al. (2012), and Popping et al. (2016), although the constraints to date are not stringent yet.

4.2. $[\text{C} \text{II}]$ Luminosity Function

We display our constraints on the $[\text{C} \text{II}]$ luminosity function at $z \simeq 6$ in Figure 6. As with the case of CO luminosity...
functions, we only plot the best-fitting case. In the same plot, we also show the predictions based on semi-analytical cosmological models by Popping et al. (2016) and observational results of ASPECS (Aravena et al. 2016) and Hayatsu et al. (2017). As with the case of the CO luminosity functions, we show the results of the ASPECS data reanalysis (see Section 4.1 for details). We also plot the observed [C II] luminosity function at $z = 0$ observed by the Herschel Space Observatory (Hemmati et al. 2017).

Although the upper limits are significantly higher than the prediction of Popping et al. (2016), our results are still consistent with previous observational results (Figure 6). Indeed, recent observations suggest that the semi-analytical models underestimate the number density of [C II] emitters (e.g., Swinbank et al. 2014; Aravena et al. 2016; Miller et al. 2016; Hayatsu et al. 2017; Hemmati et al. 2017) at the luminosity range of $L_{\text{[C II]}} \gtrsim 10^{8} \ L_{\odot}$. Thus, our results support previous observations at the luminosity range of $L_{\text{[C II]}} \sim 10^{8}$–$10^{10} \ L_{\odot}$.

Popping et al. (2016) predicted that the [C II] luminosity function at $z = 6$ returns to a level similar to that of $z = 0$. This is also suggested by observational studies (e.g., Aravena et al. 2016; Hemmati et al. 2017), regardless of [C II] luminosity function shape. As shown in Figure 6, our results are also consistent with the prediction.

Figure 4. Effective (i.e., real) co-moving survey volume as a function of intrinsic 1$\sigma$ sensitivities. Blue shaded regions indicate model uncertainties (see Section 4 for details).
comparison of our blind line emitter search with the empirically derived CO luminosity functions and previous observations. Our results are presented as red symbols. Black solid lines, green dashed lines, and blue dotted–dashed lines are the empirically derived CO luminosity functions from Oberschok et al. (2009a, 2009b), Lagos et al. (2012), and Popping et al. (2016), respectively. Cyan shaded regions are the results of the ASPECS (Decarli et al. 2016). Yellow symbols are the results of our reanalysis of the ASPECS data (see Section 4.1).

![Figure 5](image)

Comparison of our blind line emitter search with the empirically derived CO luminosity functions and previous observations. Our results are presented as red symbols. Black solid lines, green dashed lines, and blue dotted–dashed lines are the empirically derived CO luminosity functions from Oberschok et al. (2009a, 2009b), Lagos et al. (2012), and Popping et al. (2016), respectively. Cyan shaded regions are the results of the ASPECS (Decarli et al. 2016). Yellow symbols are the results of our reanalysis of the ASPECS data (see Section 4.1).

5. Summary and Conclusion

We carried out a blind search for millimeter line emitters using ALMA band 6 data with a single-frequency tuning toward four gravitational lensing clusters. We did not detect any line emitters with a peak S/N > 5, although we did find one line emitter candidate (RXJ1347-emitter1) with a peak S/N = 4.5 in the 60 MHz binning data cube.

We placed upper limits on the CO(3–2), CO(4–3), and CO (5–4) luminosity functions at z ≈ 0.3, 0.7, and 1.2, respectively. Because of the magnification effect of gravitational lensing clusters, the new data provide the first constraints on the CO and [C II] luminosity functions at unprecedentedly low luminosity levels, i.e., down to ≲ 10^{-3}–10^{-1} Mpc^{-3} at L_{CO} ∼ 10^8–10^{10} K km s^{-1} pc^2. These results are consistent with the predictions of semi-analytical models. Our constraint is comparable to the latest results of the ALMA spectroscopic scan observation of ASPECS at similar luminosity ranges (L_{CO} ∼ 10^9 K km s^{-1} pc^2). However, we can expand the range of luminosity to >0.5 dex lower than previous observations. Our constraint on the evolution of CO luminosity function between z = 0 and z ≈ 1 is consistent with the predictions of semi-analytical models by Oberschok et al. (2009a, 2009b), Lagos et al. (2012), and Popping et al. (2016), although the constraints to date are not yet stringent.

We also placed upper limits on the [C II] luminosity function at z ≈ 6. Although the upper limits are significantly higher than the prediction of the semi-analytical model, our results are still consistent with previous observational results. Our results are consistent with the scenario that the [C II] luminosity function returns to a level similar to that of z = 0 at z ≈ 6.

The total observation time of our data is comparable with ASPECS (∼20 hr at Band 6). Therefore, this study demonstrates that not only the spectroscopic scan observations, but also the wide observations with a single-frequency tuning toward gravitational lensing clusters are useful for constraining the CO and [C II] luminosity functions. We will also be able to apply stronger constraints by adding more ALMA Cycle 3 or 4 data toward gravitational lensing clusters, which will become public soon.

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Appendix

A.1. Line Emitter Candidate: “RXJ1347-emitter1”

We find a line emitter candidate at \((\alpha_{2000}, \delta_{2000}) = (13^h47^m30^s13, -11^\circ45'26''59)\). In Figure 7, we display the spectrum of RXJ1347-emitter1. RXJ1347-emitter1 is detected with S/N = 4.5 at the peak channel and with S/N = 4.3 at next to the peak channel in the 60 MHz binning data. In the 100 MHz binning data, it is detected with S/N = 5.8 at the peak channel. Although the negative tail of the noise distribution of the 60 MHz binning data extends to S/N = −4.5, we do not detect any pixels with S/N < −5.8 in the 100 MHz binning data. We have no atmospheric absorption lines around the peak frequency of RXJ1347-emitter1. There are no astronomical absorption features in the 3D data cubes of bandpass calibrators.

As shown in Figure 8, RXJ1347-emitter1 has no counterpart at optical/NIR wavelengths. Thus, RXJ1347-emitter1 can be a \([\text{C II}]\) 158 \(\mu\)m emitter at \(z = 5.95\) rather than a CO emitter at \(z \sim 1\), if it is a real line emitter. To confirm whether RXJ1347-emitter1 is a real detection or a spurious detection and determine redshift, future ALMA follow-up observation is needed.

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