SERENDIPITOUS ALMA DETECTION OF A DISTANT CO-EMITTING GALAXY WITH A BURIED ACTIVE GALACTIC NUCLEUS BEYOND THE NEARBY MERGING GALAXIES VV114
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ABSTRACT

We report the detection of a distant star-forming galaxy, ALMA J010748.3−173028, which is identified by a 13σ emission line at 99.75 GHz ($S\Delta v = 3.1$ Jy km s$^{-1}$), behind the nearby merging galaxies VV114 using the Atacama Large Millimeter/submillimeter Array (ALMA) Band 3. We also find an 880-μm counterpart with ALMA Band 7 ($S_{880\mu m} = 11.2$ mJy). A careful comparison of the intensities of the line and the continuum suggests that the line is a redshifted $^{12}$CO transition. A photometric redshift analysis using the infrared to radio data favors a CO redshift of $z = 2.467$, although $z = 3.622$ is acceptable. We also find a hard X-ray counterpart, suggesting the presence of a luminous ($L_X \sim 10^{44}$ erg s$^{-1}$) active galactic nucleus obscured by a large hydrogen column ($N_H \sim 2 \times 10^{23}$ cm$^{-2}$ if $z = 2.47$). A cosmological simulation shows that the chance detection rate of a CO-emitting galaxy at $z > 1$ with $\geq 1$ Jy km s$^{-1}$ is $\sim 10^{-3}$ per single ALMA field of view and 7.5-GHz bandwidth at 99.75 GHz. This demonstrates that ALMA has sufficient sensitivity to find an emission-line galaxy such as ALMA J010748.3−173028 even by chance, although the likelihood of stumbling across such a source is not high.

Subject headings: galaxies: formation — galaxies: starburst — quasars: general — submillimeter: galaxies — X-rays: galaxies

1. INTRODUCTION

In recent years, the advent of new millimeter (mm) and submillimeter (submm) facilities, such as the Atacama Large Millimeter/submillimeter Array (ALMA), with unprecedented sensitivity and frequency coverage, has improved the detectability of cool gas in high-redshift star-forming galaxies (e.g., Wagg et al. 2012, Vieira et al. 2012, Blain et al. 2002, for a review) in [C II] 158-μm line emission during 870-μm continuum follow-up observations of 126 SMGs using ALMA, which places the first constraint on the [C II] luminosity function at $z = 4.4$. Furthermore, Hatsukade et al. (2013) made the deepest unlensed number counts of SMGs using sources incidentally detected in the same fields of view (FoVs) toward near-infrared-selected star-forming galaxies at $z = 1.4$. Such “incidental” searches for high-z star-forming galaxies, especially in emission lines, offer a unique opportunity to investigate the line luminosity functions or cool gas mass functions, which are important for constraining galaxy formation models.

Here we report the serendipitous detection of a dusty starburst galaxy, ALMA J010748.3−173028 (hereafter ALMA-J0107), with a significant emission line at 99.75 GHz, which is likely a redshifted $^{12}$CO line. At this position, we find a hard X-ray source, which strongly suggests the presence of a buried active galactic nucleus (AGN).

We assume a cosmology with $\Omega_m = 0.3$, $\Omega_L = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ ($h = 0.7$).

2. ALMA OBSERVATIONS AND RESULTS

ALMA 3-mm and 880-μm observations toward VV114 (program ID: 2011.0.00467.S) were conducted using the compact configuration in November 2011 and the extended configuration in May 2012 (3-mm observation only). The correlator was configured to cover 98.53–102.35 GHz/110.77–113.90 GHz (3 mm) and 323.51–327.25 GHz/335.68–339.31 GHz (880 μm) with a 0.488 MHz resolution. The 3-mm and 880-μm primary beam sizes are 62″ and 19″, respectively; for the 880-μm observations, we mosaicked seven pointings to compensate for the small FoV of Band 7. At both 3 mm and 880 μm, Uranus, J1924–292, and J0132–169 (6° away from VV114) were used to calibrate the absolute flux, bandpass, and complex gain, respectively. We used CASA (McMullin et al. 2007) to calibrate the visibility data and to image them with a robust weighting of 0.5. Note that we made the continuum images using only spectral channels that are free from $^{12}$CO emission from VV114, which leaves 6.7-GHz and 6.6-GHz bandwidths at 3 mm and 880 μm, respectively. We cleaned the resulting dirty images down to the 1σ level. The synthesized beam sizes at 3 mm and 880 μm are 2″37 × 1″57 (PA = 94°) and 1″33 × 1″12 (PA = 120°), respectively. The resulting rms noise levels at 3 mm before correcting for primary beam attenuation were 0.92 mJy beam$^{-1}$ for a cube with a resolution of 30 km s$^{-1}$ and 50 μJy beam$^{-1}$ for the continuum image. The 880-μm noise levels for a 30 km s$^{-1}$
The integrated intensity is 3σ, where \( \sigma \) is the noise level corrected for primary beam attenuation (0.14 mJy beam\(^{-1}\)) at the ALMA-J0107 position. Crosses mark positions of near-infrared peaks shown in Figure 2 of Imanishi et al. (2008). Partial large circle represents primary beam size at 99.75 GHz. Filled ellipses in bottom-left corner indicate synthesized beam sizes of emission line image (gray) and 880-µm images (black). (Top right) 100 GHz spectrum of ALMA J010748.3–173028 across the 1.875 GHz spectral window of ALMA Band 3. Flux densities are measured with a 4″ aperture and corrected for primary beam attenuation (0.79×). Inset shows closeup of the spectrum; solid curve is the best-fit Gaussian. (Bottom) 15″×15″ multiband with a separation of 4σ, where σ = 0.5 mJy beam\(^{-1}\) is the noise level corrected for primary beam attenuation (0.28×). Contours of SMA 1.3-mm image are drawn at 2σ, 3σ, and 4σ, where σ = 1.21 mJy beam\(^{-1}\).

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We serendipitously detect a 13σ line-emitting object, ALMA-J0107, at 99.753 GHz at (\( \alpha, \delta \))\( _{2000} = (01^h 07^m 48.32, -17^\circ 30' 28.1') \), as shown in Figure 1. The image is marginally resolved, and the beam-deconvolved source size measured using a CASA task imfit is 1.76 ± 0′′.2, although no velocity structure is found. Figure 1 (upper right) shows the spectrum of the emission line. A single Gaussian fit to the spectrum shows \( S_{\text{peak}} = 12.9 \pm 1.0 \) mJy, \( \Delta v = 210 \pm 18 \) km s\(^{-1}\). The integrated intensity is 3.14 ± 0.15 Jy km s\(^{-1}\). This line does not correspond to a CO line or any other line of VV114 itself, even if we search a wide velocity range of ±10000 km s\(^{-1}\) around the systemic velocity of VV114 (6100 km s\(^{-1}\)). Moreover, we find no emission line feature in the other spectral windows of Bands 3 and 7 at this position. Thus, it is natural to consider a redshifted emission line, especially a \(^{12}\)CO line, arising from a background galaxy. We list the possible redshifts, as well as the corresponding CO luminosities and molecular masses, for up to the \( J = 6-5 \) transitions of \(^{12}\)CO in Table 1. The \( J = 7-6 \) (z = 7.087) transition is ruled out because no [C I](2–1) at \( \nu_{\text{obs}} = 100.08 \) GHz is found. Higher transitions at \( z \geq 8.2 \) are not plausible.

We will identify the line in § 3.

The 880-µm continuum emission in Band 7 is detected at the same position as the Band 3 line peak, close to the edge of the ALMA FoV (Figure 1 top left). The 880-µm flux density is 11.2 ± 0.4 mJy after correcting for primary beam attenuation, whereas we fail to detect the 3-mm continuum in Band 3 down to the 3σ upper limit of \(< 0.19 \) mJy. The flux density is typical of SMGs (Blain et al. 2002), and the inferred far-infrared (FIR) luminosity is \( L_{\text{FIR}} \approx 1 \times 10^{11} L_{\odot} \) for \( 1 < z < 10 \) if we assume a dust temperature of \( T_{\text{dust}} = 40 \) K and an emissivity index of \( \beta = 1.5 \). If the FIR luminosity is powered by starburst activities, a star formation rate is estimated to be \( \sim 2 \times 10^{4} M_{\odot} \) yr\(^{-1}\) following Kennicutt (1998). We also find 1.3-mm continuum emission in published Submillimeter Array (SMA) data (Wilson et al. 2008). The 1.3-mm flux density is 5.2 ± 1.3 mJy. The Rayleigh–Jeans slope is constrained primarily by the ALMA observations, and the lower limit of the spectral index is \( \alpha = 3.5 \), consistent with those found in dusty star-forming galaxies.

At the ALMA position, many ancillary data are available from the radio to the X-ray bands. Table 2 lists the results of multiwavelength photometry, and Figure 2...
Distant CO-emitting galaxy beyond VV114

Table 1  
| Line Identification |
|---------------------|
| 12CO Transition | $z$ | $L'_{\text{CO}}$ | $M(\text{H}_2)$ | Predicted $S_{\text{CO}}\Delta v$ |
|------------------|-----|----------------|-----------------|------------------------|
| $J = 1 \rightarrow 0$ | 0.1556 | 0.37 | 0.29 | 0.6 | 1.1 |
| $J = 2 \rightarrow 1$ | 1.311 | 7.1 | 5.7 | 0.8 | 1.6 |
| $J = 3 \rightarrow 2$ | 2.467 | 9.9 | 7.9 | 1.1 | 2.4 |
| $J = 4 \rightarrow 3$ | 3.622 | 10.5 | 8.4 | 1.4 | 3.5 |
| $J = 5 \rightarrow 4$ | 4.777 | 10.4 | 8.3 | 1.7 | 4.9 |
| $J = 6 \rightarrow 5$ | 5.932 | 10.0 | 8.0 | 2.0 | 6.6 |

$^a$ CO line luminosity in units of $10^{16}$ K km s$^{-1}$ pc$^2$  
$^b$ Molecular gas mass in units of $10^9$ $M_\odot$, derived using a conversion factor of $0.8 M_\odot$ (K km s$^{-1}$ pc$^2$) $^{-1}$ (Browne & Solomon 1999) and assuming thermally excited lines  
$^c$ Integrated intensity in units of Jy km s$^{-1}$  
$^d$ $T_{\text{dust}} = 40$ K, $J = 1.5$, and the CO excitation ladder of M82 (Weiβ et al. 2005b) are assumed.  
$^e$ The same as (b), but a dust temperature of 50 K and the CO excitation ladder of BR 1202−0725 SE (Salomé et al. 2012) are assumed.

Table 2  
| Multiwavelength Counterparts to ALMA-J0107 |
|---------------------|
| Instrument | Band | Flux Density | Unit |
|-------------|------|--------------|------|
| VLA$^a$ | 3.0 cm | $< 0.3$ (3σ) | mJy |
| ALMA/Band 3 | 3.0 mm | $< 0.19$ (3σ) | mJy |
| SMA | 1.3 mm | 5.2±1.3 mJy |
| ALMA/Band 7 | 880 μm | 11.2±0.4 mJy |
| Spitzer/IRAC | 8.0 μm | $< 0.1$ mJy |
| Spitzer/IRAC | 5.8 μm | $< 0.1$ mJy |
| Spitzer/IRAC | 4.5 μm | 0.06±0.01 mJy |
| Chandra/ACS | 0.5–10 keV | 2.73×10$^{-15}$ erg s$^{-1}$ cm$^{-2}$ |
| Chandra/ACS | 0.5–2 keV | 8.34×10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ |
| Chandra/ACS | 2–10 keV | 1.90×10$^{-15}$ erg s$^{-1}$ cm$^{-2}$ |

$^a$ The data were retrieved from the VLA archive.  
$^b$ The flux density is strongly affected by contamination from VV114 and thus should be regarded as an upper limit.

3.2. Line Identification

To confirm that this is a 12CO line, we estimate the 12CO intensities using the 880-μm continuum intensity and some empirical relations and quantities found in a local starburst galaxy, M82. From the 880-μm flux density, we obtain $L'_{\text{CO}} \sim 9 \times 10^{12} L_\odot$ for $z > 1$ and $L'_{\text{CO}} \sim 1 \times 10^{12} L_\odot$ for $z = 0.156$ if $T_{\text{dust}} = 40$ K and $\beta = 1.5$. The inferred FIR luminosity is almost independent of the redshift at $z > 1$. Although these are very crude estimates, we use the $L'_{\text{CO}}$ and the $L'_{\text{CO}}= L_{\text{CO}}(3–2)$ correlation (Iono et al. 2009) to obtain $12CO(3–2)$ luminosity and then the intensities at the possible redshifts. We find that $S_{\text{CO}}(3–2) = 3.9$, 1.6, 1.1, 1.0, 0.98, and 1.0 Jy km s$^{-1}$ at $z = 0.156$, 1.31, 2.47, 3.62, 4.78, and 5.93, respectively. Then we assume the CO excitation ladder found in M82 (Weiβ et al. 2005b) to obtain the CO intensities at other transitions, which allows us to estimate those at the possible redshifts. We repeat this procedure for a higher dust temperature ($T_{\text{dust}} = 50$ K) and the CO excitation found for BR1202−0725 SE (Salomé et al. 2012), in which the heating of the interstellar medium is dominated by a powerful AGN. The results are given in Table 1. The line intensities are on the order of 1 Jy km s$^{-1}$ and are in good agreement with the observed ones, strongly suggesting that the line is 12CO because non-12CO lines, such as 13CO and HCN, are $\geq 1$ order(s) of magnitude weaker than 12CO. The atomic carbon [CII](1–0) line is possible (at $z = 3.93$) but less likely because the intensity is typically 1/3 to 1/10 that of 12CO(3–2) (e.g., Weiβ et al. 2005b).

Other possible line attributions include the H2O molecule, which is known to have emission lines as bright as those of 12CO in the submm band. The major transitions exhibiting strong emission at $\nu_{\text{rest}} < 1000$ GHz are $J_{K_a-K_c} = 2_{11}-2_{02}$ and $2_{02}-1_{11}$ at $\nu_{\text{rest}} = 752.0$ and 987.9 GHz, respectively. However, the redshifts inferred from the H2O lines would be 6.54 and 8.90, which are outside of the photometric redshift range. Therefore, these results in combination with the photometric redshift indicate that the line is most likely a redshifted 12CO transition at $z = 2.467$ or 3.622.

4. HARD X-RAY DETECTION

We used the primary package of Chandra/ACIS-I data (sequence No. 600501, observation ID: 7063). The X-ray
source at the ALMA position also appears 10′′ east of VV114E in Figure 6 of Grimes et al. (2006). The effective exposure time at the position of ALMA-J0107 was 59 ks. We count the X-ray events with a 4′′-diameter aperture and measure the background level over a 2′-diameter circular region centered at ALMA-J0107 while masking VV114 and ALMA-J0107. We find ∼100 counts within the aperture, and background subtraction leaves ∼35 counts, which is poor statistics but just enough to simply model the spectrum. We use xspec (version 12.8.1, Arnaud 1996) for spectral modeling and assume a power-law spectrum for the intrinsic spectrum.

For simplicity, we consider only an absorbed spectrum with the intrinsic photon index (\(\Gamma\)) and obscuring column density (\(N_{\text{H}}\)) as free parameters, and eliminate other components such as the scattered spectrum. Note that this simple assumption may underestimate the obscuring column.

The results for the likely redshifts of \(z = 2.47\) and 3.62, as well as for \(z = 1.31\) for reference, are shown in Table 3. The inferred unabsorbed luminosity, \(L_X\), covers the range 43.5 \(\leq \log(L_X/\text{erg s}^{-1}) \leq 44.6\) for \(1.31 \leq z \leq 3.62\), which is comparable to that of \(z \sim 2\) AGN-classified SMGs (Alexander et al. 2005). Using the method described in Tamura et al. (2010), we estimate an AGN bolometric luminosity of \(L_{\text{bol}} \sim (0.8-34) \times 10^{11} L_\odot\) for \(1.31 \leq z \leq 3.62\). Despite a large uncertainty, this gives a mass of \((0.1-5) \times 10^7 (M_{\text{Edd}}/0.2)^{-1} M_\odot\) for the accreting supermassive black hole, where \(M_{\text{Edd}}\) is the Eddington ratio, which is typically 0.2-0.6 in SMGs (Alexander et al. 2008). The bolometric luminosity is comparable to those found in the most luminous AGNs in the local Universe (e.g., Mrk 231), but it is even less than the FIR luminosity of the host galaxy ALMA-J0107 (\(L_{\text{FIR}} \sim 9 \times 10^{12} L_\odot\) for \(T_{\text{dust}} = 40\) K), suggesting that the large FIR luminosity of ALMA-J0107 is not dominated by the AGN but can be attributed to massive star formation activities.

### 5. NUMBER COUNTS OF CO EMITTERS

How frequently is a \(\approx 3\) Jy km s\(^{-1}\) \(^{12}\)CO emitter observed by chance? We use a mock galaxy catalog from the s\(^3\) SAX simulation (Obreschkow et al. 2009a,b) to estimate the expected number of detections of redshifted \(^{12}\)CO, regardless of redshift, with a single pointing/tuning of ALMA at 100 GHz. This is a semi-analytic simulation of neutral atomic (\(\text{H}\)) and molecular (\(\text{H}_2\)) hydrogen in galaxies and the associated CO lines; it is based on the Millennium Simulation (Springel et al. 2005), which reliably recovers galaxies with cold hydrogen masses \(M(\text{H+H}_2) > 10^8 M_\odot\). It reproduces the local CO(1–0) luminosity function well (Keres et al. 2003), whereas those at high-z are not fully verified by observations; It may underestimate the number density of \(\sim 0.6\) Jy km s\(^{-1}\) CO emitters at \(z \sim 1.5\) by a factor of several, in comparison with CO observations of \(z \sim 1.5\) BzK galaxies (Daddi et al. 2008, 2010). The cumulative number counts of CO emitters, \(N(>S\Delta v)\), expected in a bandwidth \(dv_{\text{obs}}\) and a primary beam solid angle \(d\Omega\) are described as

\[
N(>S\Delta v) = \sum_{J=1}^{\infty} \left( \frac{dN}{dz} \right)_{z_J} dz d\Omega
\]

\[
= \frac{d\nu_{\text{obs}}}{\nu_{\text{obs}}} \int_{\nu_{\text{obs}}}^{\infty} \sum_{J=1}^{\infty} \left( \frac{dN}{dz} \right)_{z_J} (1 + z_J),
\]

where \(z_J\) is the redshift at which the \(J \rightarrow J-1\) transition of CO is observed at \(\nu_{\text{obs}}\), and \((dN/dz)_{z_J}\) is the surface...
number density of galaxies observed in the \( J \rightarrow J - 1 \) transition per redshift interval with line fluxes above a certain threshold, \( S_{\lambda} \). To estimate \( dN/dz \) at each \( z_f \), we extract sources with an integrated intensity higher than 1 Jy km s\(^{-1}\) from the simulated volumes defined by an area of 62.5 \( \times \) 62.5 h\(^{-2}\) Mpc\(^{2}\) with a depth of \( \Delta z = 0.50 \) at \( z = 1.31, 2.47, 3.62, 4.78, \) and 5.93 (we choose \( \Delta z = 0.10 \) for \( z = 0.156 \).

Consequently, we expect \( \approx 0.011 \) source with \( > 1 \) Jy km s\(^{-1}\) per ALMA FoV (2800 arcsec\(^2\)) and bandwidth (7.5 GHz). Most of the sources (\( \approx 90\% \)) are CO(1–0) at \( z = 0.156 \). The remaining 10\% are almost evenly distributed at \( z = 1.31, 2.47, \) and 3.62, but no source is found at \( z \geq 4.78 \). The SED analysis (\( \S 3.4 \)) rules out the lowest redshift (\( z = 0.156 \)), even though the probability of a chance detection appears to be highest for \( z = 0.156 \). Although it should be properly tested whether the \( s^{0} \) SAX simulation reproduces the brightest (\( > 1 \) Jy km s\(^{-1}\)) population of CO emitters at \( z > 1 \), this result implies that ALMA-J0107, likely at \( z = 2.47 \) or 3.62, is a very rare galaxy that falls within the ALMA bandwidth by chance (one out of \( \approx 1000 \) FoVs).

6. SUMMARY

We presented the detection of a \(^{12}\)CO-emitting galaxy, ALMA-J0107, beyond the nearby merging galaxies VV114. The integrated intensity of CO and the 880-\( \mu \)m flux density are 3.14 \( \pm \) 0.15 Jy km s\(^{-1}\) and 11.2 \( \pm \) 0.5 mJy, respectively. The photometric redshift analysis favors \( z = 2.467 \), but \( z = 3.622 \) is acceptable. The molecular mass and FIR luminosity at the plausible redshifts are \( M(H_2) \sim 8 \times 10^{10} M_\odot \) and \( L_{\text{FIR}} \sim 1 \times 10^{13} L_\odot \), respectively, which correspond to a star formation rate of \( \sim 2000 M_\odot \) yr\(^{-1}\). We identified a hard X-ray source at the ALMA position, suggesting the presence of a luminous (\( L_X \sim 10^{44} \) erg s\(^{-1}\)) AGN behind a large hydrogen column (\( 23.2 \lesssim \log [N_{\text{H}}/\text{cm}^{-2}] \lesssim 23.6 \) for the likely redshifts). However, the intrinsic properties of the AGN (e.g., the bolometric luminosity) depend strongly on the redshift, although the FIR luminosity and molecular mass are rather insensitive to the redshift. This fact makes it difficult to investigate the power source of ALMA-J0107 and the evolutionary status of black hole growth in ALMA-J0107. It is obviously quite important to confirm the redshift through observations of the other transitions of \(^{12}\)CO.

This serendipitous detection of a CO-emitting galaxy demonstrates that ALMA is capable of identifying an emission-line galaxy such as ALMA-J0107. We have shown that the likelihood of stumbling across such a source is not high, and redshift determination remains a challenge even when one line and the continuum are clearly detected. Nevertheless, \( ~1000 \) pointings of ALMA Band 3 will offer an additional detection of a \( > 1 \) Jy km s\(^{-1}\) CO source at high redshift (\( z > 1 \)). A CO emitter at this flux level can routinely be detected at 100 GHz in only a few minutes with the full ALMA if the line happens to fall in the observing band. A complete census of background high-\( z \) CO emitters in Band 3 archival cubes, as well as \([ \text{C} \equiv \text{II}] \) emitters in Band 6/7, is encouraged.

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