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ALMA Reveals Strong [C II] Emission in a Galaxy Embedded in a Giant Lyα Blob at z = 3.1

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Abstract

We report the result from observations conducted with the Atacama Large Millimeter/submillimeter Array (ALMA) to detect [C II] 158 µm fine structure line emission from galaxies embedded in one of the most spectacular Lyα blobs (LABs) at z = 3.1, SSA22-LAB1. Of three dusty star-forming galaxies previously discovered by ALMA 860 µm dust continuum survey toward SSA22-LAB1, we detected the [C II] line from one, LAB1-ALMA3 at z = 3.0993 ± 0.0004. No line emission was detected, associated with the other ALMA continuum sources or from three rest-frame UV/optical selected zspec ≳ 3.1 galaxies within the field of view. For LAB1-ALMA3, we find relatively bright [C II] emission compared to the infrared luminosity (L[CII] = LIR ≈ 0.01) and an extremely high [C II] 158 µm and [N II] 205 µm emission line ratio (L[CII]/L[N II] > 55). The relatively strong [C II] emission may be caused by abundant photodissociation regions and sub-solar metallicity, or by shock heating. The origin of the unusually strong [C II] emission could be causally related to the location within the giant LAB, although the relationship between extended Lyα emission and interstellar medium conditions of associated galaxies is yet to be understood.

Key words: galaxies: evolution – galaxies: halos – galaxies: high-redshift – galaxies: ISM – submillimeter: galaxies

1. Introduction

Investigating the physical and chemical properties of the interstellar medium (ISM) of dusty star-forming galaxies and/or high-redshift galaxies has been difficult, as typical UV/optical nebular lines are not useful due to heavy dust extinction and/or the lines are not accessible with conventional ground-based instruments. Recently, the Atacama Large Millimeter/submillimeter Array (ALMA) has opened a new window, allowing us to exploit fine structure lines at rest-frame far-infrared (FIR) wavelengths to diagnose the ISM properties for these galaxy populations (e.g., Nagao et al. 2012; Decarli et al. 2014; Inoue et al. 2016). The [C II] 158 µm (2P23/2 → 2P13/2) is known to be the dominant coolant of the ISM and one of the brightest lines from star-forming galaxies in the FIR (e.g., Israel et al. 1996). While the [C II] emission arises primarily from dense photodissociation regions (PDRs), it is also observed in various regions/environments, including ionized regions, cool, diffuse interstellar gas, and shocked gas (e.g., Stacey et al. 1991; Madden et al. 1993; Nagao et al. 2011; Appleton et al. 2013).

In order to characterize the [C II] emission and investigate the nature of the ISM in star-forming galaxies at high redshift, Lyα blobs (LABs) are a useful laboratory. LABs are extended gaseous nebulae, preferentially found in regions of galaxy overdensities in the distant universe (e.g., Steidel et al. 2000; Matsuda et al. 2004; Yang et al. 2009). A large number of LABs are associated with star-forming galaxies such as submillimeter galaxies (SMGs; e.g., Geach et al. 2005, 2014; Umehata et al. 2015, 2016), distant red galaxies (DRGs; e.g., Erb et al. 2011; Uchimoto et al. 2012; Kubo et al. 2013), and Lyman break galaxies (LBGs; e.g., Matsuda et al. 2004). Thus, LABs are likely to be the sites of ongoing massive galaxy formation and assembly, and the extended gaseous structures around them are believed to be observational signs of large-scale gas flows (inflow/outflow) and their interactions as well as photoionization (e.g., Taniguchi & Shioya 2000; Mori &
Umehara 2006; Dijkstra & Loeb 2009). SSA22-LAB1 (hereafter LAB1; Steidel et al. 2000) is a giant LAB discovered in the \( z = 3.1 \) SSA22 proto-cluster region and one of the most well-studied LABs (e.g., Chapman et al. 2004; Hayes et al. 2011; Geach et al. 2014; Kubo et al. 2015). The unique environment makes LAB1 a useful laboratory for investigating the [C II] emission from growing galaxies in the early universe. Throughout the Letter, we adopt a cosmology with \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\).

2. Observations and Data Reduction

We observed LAB1 with ALMA in band 8 as a part of an ALMA cycle-2 program (ID: 2013.1.00159.S; PI: Umehata), targeting the [C II] 158 \( \mu \)m transition (\( \nu_{\text{rest}} = 1900.537 \) GHz, redshifted to 463.55 GHz or 647 \( \mu \)m, at \( z = 3.100 \)). As shown in Figure 1, the field of view (FoV) at \(~464 \) GHz is large enough to cover the majority of the Ly\( \alpha \) emitting region (\( d \sim 13\,\text{kpc} \) at \( z = 3.1 \)) and contains three 860 \( \mu \)m continuum ALMA sources: LAB1-ALMA1, LAB1-ALMA2, and LAB1-ALMA3 (hereafter ALMA1, ALMA2, and ALMA3, respectively; Geach et al. 2016).\(^{20}\) ALMA3 is spatially coincident with a DRG at \( z_{\text{spec}} = 3.1 \) (Kubo et al. 2015). While ALMA1 and ALMA2 do not have spectroscopic redshifts, their photometric redshifts and the low probability of chance association of ALMA sources suggest a physical association between the two ALMA sources and the giant Ly\( \alpha \) nebula (Uchimoto et al. 2012; Y. Matsuda et al. 2017, in preparation). Three other galaxies at \( z_{\text{spec}} \approx 3.1 \) (an LBG, a K-band selected galaxy, and an [O III] emitter) are also located within the band 8 FoV (Figure 1).

Observations were carried out on 2015 June 16 using a spectral scan mode with the FDM correlator mode to cover the redshift range of the proto-cluster, \( z = 3.06 - 3.12 \) (Matsuda et al. 2005). Among four planned spectral windows, only two were actually executed. The incomplete observation resulted in frequency coverage of 461.03–462.78 GHz and 462.91–464.66 GHz (\( \nu_{\text{[C II]}} = 3.090–3.105, 3.107–3.122 \)) after flagging the edge channels. The array configuration was C34-5 and the baseline lengths were 21–784 m. The on-source time was 4.5 minutes. Ceres was observed for amplitude calibration, and the quasar J2148+0657 was utilized for bandpass and phase calibration. The data were processed with the Common Astronomy Software Application (CASA) ver. 4.4.0 (McMullin et al. 2007). The cube was first created with the natural weighting using the CASA task, CLEAN. The resultant cube (hereafter “full cube”) has a typical synthesized beam FWHM of 0.27 × 0.26 (P.A. 46°). We also created a “tapered” cube adopting the taper parameter, outer taper = 0.5 arcsec, which has a typical synthesized beam, 0.45 × 0.42 (P.A. –70°). The typical rms level is \( \approx 3.5 \) mJy beam\(^{-1}\) at the phase center per 80 km s\(^{-1}\) channel in the tapered cube. To search for band 8 continuum sources, we created a “tapered” continuum map at 463 GHz, using the line-free channels. The “dirty” map has an rms level of 0.8 mJy beam\(^{-1}\) at the phase center, and none of the sources is found above 5\( \sigma \).

LAB1 has also been observed by ALMA in band 7. One program (ID. 2013.1.00704.S; PI: Matsuda) covered the redshifted [N II] 205 \( \mu \)m transition line (\( \nu_{\text{rest}} = 1461.131 \) GHz, redshifted to 356.37 GHz, at \( z = 3.100 \); Y. Matsuda et al. 2017, in preparation). The typical noise rms at 0.55 resolution, which is equivalent to the “tapered” cube in band 8, is \( \approx 0.4 \) mJy beam\(^{-1}\) at the phase center, per 80 km s\(^{-1}\) channel.

3. Results

3.1. [C II] 158 \( \mu \)m in LAB1-ALMA3

We detected [C II] emission from one of the three dusty star-forming galaxies, ALMA3 (Figures 2 and 3). Figure 3 shows the [C II] spectrum. A Gaussian fit to the line has \( z = 3.0993 \pm 0.0004 \) with FWHM 275 ± 30 km s\(^{-1}\). Kubo et al. (2015) reported a redshift of \( z = 3.1000 \pm 0.0003 \) on the basis of H\( \beta \) and [O III] \( \lambda \)5007 lines, and hence our measurement is consistent (the velocity offset is within \( \sim 50 \) km s\(^{-1}\) and the two measurements are consistent within errors). Figure 2 shows the velocity-integrated [C II] intensity and velocity maps, compared to the rest-frame 210 \( \mu \)m continuum emission.

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\(^{20}\) ALMA1, ALMA2, and ALMA3 correspond to SSA22-LAB01 ALMA b, SSA22-LAB01 ALMA a, and SSA22-LAB01 ALMA c in Geach et al. (2016), respectively.
Figure 2. Images of LAB1-ALMA3. The size of each map is 3" × 3", (a) The velocity-integrated map of the [C II] emission. The background map is the "tapered" map (0″53 FWHM; magenta contours), while we also show the "full" map (0″27 FWHM; blue contours) for comparison. Contours start at ±2σ, with steps of 1σ for both. (b) The velocity map of the [C II] emission, blanked at 2.5σ. Velocities are relative to the [O III] peak (see also Figure 3), and velocity contours are shown in steps of 80 km s⁻¹. (c) The "tapered" band 7 continuum map (0″55 FWHM), which presents rest-frame 210 μm continuum emission. Contours are plotted from ±2σ in steps of 1σ. For comparison, we also show contours of the tapered [C II] map presented in panel (a). (d) The HST STIS optical image, compared to the [C II] emission. (e) The "tapered" [N II] map. Contours are ±2σ. [C II] emission is same as other panels.

Figure 3. [C II] spectrum of LAB1-ALMA3, integrated over a region of d = 1″ in the tapered cube after correcting for the primary-beam response. We also show the redshifts and errors determined from [C II] (red lines) and [O III]/Hβ (green lines) detections. Velocities are relative to the [O III]/Hβ redshift (z = 3.1000 ± 0.0003; Kubo et al. 2015). [C II] emission from ALMA3 is detected at consistent redshift (z = 3.0993 ± 0.0004) with FWHM of 270 ± 30 km s⁻¹. The velocity range used to create the images in Figure 2 is indicated below the spectrum.

(Y. Matsuda et al. 2017, in preparation; Geach et al. 2016). HST STIS optical image (Chapman et al. 2003), and [N II] image. The [C II] emission is spatially resolved as shown in Figure 2(a), while the [C II] emission has a modest signal to noise ratio and the various clumps seen are not significant. The [C II] velocity map (Figure 2(b)) also shows complexity, which is not likely to be produced by a simple rotating disk. The position of [C II] emission is generally consistent with those of dust continuum and stellar emission.

To describe the properties of [C II] emission from the whole galaxy, we use the tapered map. A two-dimensional elliptical Gaussian fit yields a deconvolved FWHM of (0″62 ± 0″07) × (0″55 ± 0″10), which corresponds to 4.8 × 4.3 kpc². For comparison, we similarly measured the size of the dusty starburst core using the band 7 continuum image at 0″35 resolution. The yielded size is (0″53 ± 0″14) × (0″40 ± 0″12) (4.1 × 3.1 kpc²). The measured integrated line flux is I_{[C II]} = 16.8 ± 2.1 Jy km s⁻¹ and hence the line luminosity is L_{[C II]} = (5.7 ± 0.7) × 10⁶ L☉ (Table 1). The infrared (IR; 8–1000 μm) luminosity of ALMA3 is derived using an average SMG template from the ALESS survey (Swinbank et al. 2014) scaled to the 860 μm flux density, S_{860 μm} = 0.73 ± 0.05 mJy (Geach et al. 2016); L_{IR} ≈ 5.8 ± 0.4 × 10¹¹ L☉, so that L_{[C II]}/L_{IR} ≈ 0.010 ± 0.001. (We note that the IR luminosity may have larger uncertainty. Geach et al. 2016 estimated it in the range L_{IR} ≈ (0.2–1.5) × 10¹² L☉ using varying templates.) We also derived the dynamical mass of ALMA3, M_{dyn,vir} ≈ 1.0 × 10¹¹ M☉, using an isotropic virial estimator (e.g., Engel et al. 2010) on the basis of the line width and [C II] size (major axis measured from the FWHM).

We also searched for [N II] 205 μm emission from ALMA3, which resulted in non-detection (Figure 2(e)). Utilizing the [N II] map at 0″55 resolution, we obtained a δσ (point-source) upper limit on its line intensity, I_{[N II]} < 0.35 Jy km s⁻¹ and thus L_{[N II]} < 9.4 × 10⁷ L☉, and L_{[C II]}/L_{[N II]} > 61. The [N II] upper limit can slightly be relaxed when the [N II] 205 μm emission has larger extent compared to the size of the synthesized beam. If we use the other tapered [N II] map at 0″64 resolution, which is comparable to the measured [C II] size of ALMA3, we will have I_{[N II]} < 0.39 Jy km s⁻¹, L_{[N II]} < 1.0 × 10⁸ L☉, and L_{[C II]}/L_{[N II]} > 55, respectively. In the following discussion, we adopt the latter conservatively.

3.2. No [C II] Emission from the Remaining LAB1 Members

Except for ALMA3, no emission line is found in the band 8 cube. For ALMA1 and ALMA2, we just calculate a tentative upper limit of [C II] emission, assuming that the lines fall within our frequency coverage and the line widths are same as that of ALMA3. The IR luminosities of ALMA1 and ALMA2 are comparable to that of ALMA3 (L_{IR} ≈ 3.5 × 10¹¹ L☉ and L_{IR} ≈ 4.0 × 10¹¹ L☉, respectively). Utilizing the intensity map for ALMA3, we obtained a 3σ upper limit on their individual line intensity, I_{[C II]} < 2.3 Jy km s⁻¹, and line luminosity, L_{[C II]} < 8.0 × 10⁷ L☉. Although this is just a crude estimate and z_{spec} information is essential for further discussion, our result suggests that the L_{[C II]}/L_{IR} of ALMA1 and ALMA2 may be different from that of ALMA3. We also evaluated 3σ upper limits for the three rest-frame UV/optical

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21 The image has a pivot wavelength of 5733 Å.
22 We created the [N II] image, integrated the cube over the same velocity range of the [C II] map.
23 There might be a small offset, ~0″2, though the current data is insufficient to determine whether it is real.
24 Geach et al. (2016) reported the sum of 860 μm flux density, S_{860 μm} = 0.95 ± 0.04 mJy. We apportioned it between ALMA1 and ALMA2 according to their peak flux density at 0″35 resolution (Y. Matsuda et al. 2017, in preparation) and calculated IR luminosity in the same way for ALMA3.
ALMA3 shows one of the highest values seen to date, which indicates an enhanced
conditions responsible for [C ii] emission between ALMA3 and the majority of previously known IR-luminous galaxies. It has also been reported that some $z \sim 1$–2 ULIRGs show $L_{\text{C II}}/L_{\text{IR}}$ ratios comparable to ALMA3, although they have slightly higher $L_{\text{IR}}$ than ALMA3 (Brisbin et al. 2015). One possible explanation for elevated [C ii]–IR ratios is that the galaxies host widely spread star formation, and the UV radiation field is therefore dilute, which make the [C ii] line a more efficient coolant (see, e.g., Brisbin et al. 2015; Cicone et al. 2015 and references therein). The size of the dust continuum core in ALMA3 is 4.1 kpc, which is larger than a typical continuum size of bright SMGs at similar redshifts (2.4 kpc; Simpson et al. 2015; see also Ikarashi et al. 2015; Umehata et al. 2016). This supports that a relatively extended star-forming region in ALMA3 contributes the high [C ii]/IR ratio for ALMA3. Gas accretion from the cosmic web is expected to accumulate a large amount of molecular gas necessary to fuel such widespread star formation (Brisbin et al. 2015).

We have another clue from the [C ii] 158 $\mu$m at $z \sim 5$ (Decarli et al. 2014; Rawle et al. 2014; Béthermin et al. 2016; Pavesi et al. 2016 and references therein) and local (U)LRIRGs (Díaz-Santos et al. 2013; Zhao et al. 2016). ALMA3 shows one of the highest values seen to date, which indicates an enhanced [C ii] emission.
largest ratios ever reported (Figure 4). The $L_{\text{C II}}/L_{\text{[N II]}}$ ratio has been utilized to diagnose the ISM conditions. In particular, it is used to evaluate global trend on the fraction of [C II] emission associated with ionized regions (i.e., HII regions; e.g., Oberst et al. 2006; Decarli et al. 2014; Pavesi et al. 2016), mainly because nitrogen’s ionization potential (14.5 eV) is higher than that of hydrogen (13.6 eV) so that [N II] arises only from ionized regions. Pavesi et al. (2016) reported the expected a line ratio $L_{\text{C II}}/L_{\text{[N II]}} \sim 3.5$, for HII regions with electron density of $10^-1000 \, \text{cm}^{-3}$. If we adopt this estimate, it is expected that the contribution of ionized gas is only about $6\%$ and the vast majority of [C II] emission arises from the surface of dense PDRs and/or other regions/environments. The $L_{\text{C II}}/L_{\text{[N II]}}$ ratio is also sensitive to estimate gas metallicity (e.g., Nagao et al. 2012; Bethermin et al. 2016; Pavesi et al. 2016).

Nagao et al. (2012) suggest that the line ratio increases as metallicity decreases, considering both PDRs and HII regions in their model. The measured ratio, $L_{\text{C II}}/L_{\text{[N II]}} > 55$, favors sub-solar metallicity for the variety of densities and ionization parameters in their model. Gas accretion from the outside of ALMA3 may explain this relatively low metallicity. It is suggested that nitrogen may dominantly be in its doubly ionized state in high ionization conditions with lower dust shielding (e.g., Pavesi et al. 2016). This effect is unlikely to be significant in ALMA3 because it is detected in dust continuum.

Although it is not straightforward to identify the origin of [C II] emission more, together with these clues, the properties and location of ALMA3 may support the importance of shock on the elevated [C II] emission. Recently, some work has suggested that mechanical heating due to turbulence in shocks can contribute to [C II] emission at high redshift (e.g., Stacey et al. 2010; Appleton et al. 2013; Lesaffre et al. 2013; Brisbin et al. 2015). For instance, Appleton et al. (2013) reported that the resolved shocked regions of Stephan’s Quintet have exceptionally high [C II]–FIR ratio, and they also suggest that this could be commonplace for high-redshift galaxies. Brisbin et al. (2015) suggested that a variety of shocks, originating from major-merger, intergalactic gas accretion, and stellar outflows, might contribute to the elevated [C II] emission. ALMA3 shows complicated rest-frame UV morphologies and [C II] velocity structures (Figure 2), which is suggestive of galaxy–galaxy interaction (dust obscuration may also contribute to it). ALMA3 hosts intense star formation activity, as the dust continuum detection shows, and appears to be a relatively evolved system with large stellar mass $M_\ast \approx 10^{11} M_\odot$ (Kubo et al. 2015) comparable to the derived dynamical mass (we need to recognize both estimates contain large uncertainties). Therefore, galactic outflow may interact with intergalactic gas stream (e.g., Comuault et al. 2016). Thus, shock heating might be a contributor of [C II] emission from ALMA3.

One key question is the role of environment, since ALMA3 is located within a giant LAB, SSA22-LAB1. LAB1 resides in a remarkable proto-cluster and is associated with a number of star-forming galaxies, which may reflect the abundant gas accretion from cosmic web. The overdensity of galaxies may lead to a high frequency of galaxy–galaxy interaction. Therefore, the unique environment might account for the relatively strong [C II] line. On the other hand, if ALMA1 and ALMA2 are actually at redshifts similar to confirmed LAB1 members, the absence of detectable [C II] would mean diversity of the ISM state within a LAB. While we detected the [C II] line from a massive, dusty star-forming galaxy, much deeper observations of FIR lines like [C II] and [N II] toward a giant LAB at $z \sim 3$, which allows us to assess the ISM state in UV/optical selected galaxies (e.g., LSBGs like C11 in LAB1), is highly expected. Such surveys will give us an opportunity to estimate how the ISM in the galaxies evolve in biased regions in the early universe, through the comparison with other FIR line observations of galaxies in a biased region (e.g., AzTEC3 and LBG1 at $z = 5.3$; e.g., Riechers et al. 2014; Pavesi et al. 2016) or galaxies in general environment in the same era.

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Facility: ALMA.

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