ALMA C II 158 μm Imaging of an H I-selected Major Merger at z ∼ 4

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Abstract

We present high spatial resolution (≈2 kpc) Atacama Large Millimeter/submillimeter Array (ALMA) observations of [C II] 158 μm and dust-continuum emission from a galaxy at z = 3.7978 selected by its strong H I absorption (a damped Lyα absorber, DLA) against a background QSO. Our ALMA images reveal a pair of star-forming galaxies separated by ≈6 kpc (projected) undergoing a major merger. Between these galaxies is a third emission component with highly elevated (2 ×) [C II] 158 μm emission relative to the dust continuum, which is likely to arise from stripped gas associated with the merger. This merger of two otherwise-normal galaxies is not accompanied by enhanced star formation, contrary to mergers detected in most luminosity-selected samples. The DLA associated with the merger exhibits extreme kinematics, with a velocity width for the low-ionization metal lines of Δv90 ≈ 470 km s−1, that spans the velocity spread revealed in the [C II] 158 μm emission. We propose that DLAs with high Δv90 values are a signpost of major mergers in normal galaxies at high redshifts, and use the distribution of the velocity widths of metal lines in high-z DLAs to provide a rough estimate the fraction of z > 3 galaxies that are undergoing a major merger.

Unified Astronomy Thesaurus concepts: Galaxy mergers (608); Quasar absorption line spectroscopy (1317); Damped Lyman-alpha systems (349)

1. Introduction

At the heart of modern cosmology is the concept that large structures are built up from the collapse and agglomeration of smaller structures. This holds for both dark matter halos and the galaxies within them, which together are predicted to merge across cosmic time to yield the massive galaxies observed today. Such mergers are observed and predicted to transform the morphology of galaxies (e.g., Mišes & Hernquist 1996; Naab & Burkert 2003; Lotz et al. 2008), to dominate the mass evolution in quiescent galaxies (e.g., Bell et al. 2006), and to trigger dramatic enhancements or declines in a galaxy’s star formation rate (e.g., Somerville et al. 2001; Jogee et al. 2009; Patton et al. 2011). One is thus motivated to track the incidence and processes that govern galaxy mergers across cosmic time.

Despite these strong motivations to study mergers, empirical studies—especially in the high-z universe—are relatively scarce. Indeed, the majority of merging systems known are serendipitous discoveries (e.g., Cooke et al. 2010) or are associated with the most luminous galaxies, e.g., submillimeter galaxies with extreme star formation rates (SFRs; Oliveiras et al. 2016), or galaxies hosting ultra-luminous quasars (Neeleman et al. 2019b). There is also a set of imaging studies that statistically identify galaxies likely to merge within approximately a dynamical time (e.g., Patton et al. 1997; Bundy et al. 2009; Mantha et al. 2018). These studies are limited by the lack of spectroscopy, which means ambiguous identifications of individual mergers and, more importantly, no analysis of the system dynamics (e.g., Ellison et al. 2010).

An important exception are the analyses by Ventou et al. (2017, 2019), who used deep Very Large Telescope (VLT)/MUSE integral field spectroscopy to study mergers of sub-L∗ galaxies. These studies are, however, flux-limited and therefore prone to selection biases. Such biases could manifest in either direction, e.g., a higher inferred merger rate if gas is preferentially driven toward the central regions to ignite star formation and/or active galactic nucleus activity (e.g., Mišes & Hernquist 1996), or a lower rate if processes driving the merger enshroud the system in dust and obscure it from detection (e.g., Treister et al. 2010).

An additional tenant of our cosmological paradigm is that the rate of assembly on galaxy scales was greater in the past. Analyses of cosmological simulations report that on average major mergers (defined here as at least a 1:4 mass ratio) occur every ≈2 Gyr at z = 3 for galaxies with stellar mass M∗ ≳ 1011M⊙ (Rodríguez-Puebla et al. 2017). The merger rate is expected to increase with redshift, with mergers playing an increasingly important role in galaxy assembly at early times.

Empirically, it is challenging to assess the merger rate because we cannot directly estimate the timescale for these events from the “static” observations afforded on human timescales. Instead, the majority of studies have focused on the fraction of galaxies in a population that are interacting and/or likely to undergo a major merger, fMM. fMM is frequently defined as the fraction of galaxies with projected physical separation 8R ≤ 25 kpc and velocity offset Δv < 500 km s−1. The current literature reports a low major merger fraction today (fMM ≈ 0.01; Xu et al. 2012), with a rise from z = 0 to z ≈ 2, peaking at fMM ≈ 2 (López-Sanjuan et al. 2013; Ventou et al. 2017, 2019). At high redshifts (z > 2), the results are drawn solely from VLT/MUSE surveys of Ventou et al. (2017, 2019), which report a surprising decline in fMM at z > 2, in apparent contradiction with the theoretical rise in the accretion rate. This apparent conundrum has been resolved by...
recognizing that the time to merge is much shorter in the high-density environment of the high-z universe. Interpretations aside, this provides a limited data set to examine the merger fraction and/or the detailed impacts of the merging process on high-z galaxies.

Over the past few years, we have used the Atacama Large Millimeter/submillimeter Array (ALMA) to search for redshifted [C II] 158\,\mu m emission from a sample of H I-selected galaxies at z \gtrsim 4 (Neeleman et al. 2017, 2019a). These galaxies were targeted because of their association with a high column density of H I (N_HI), identified as a damped Ly\alpha absorber (DLA; Wolfe et al. 2005) in a background quasar spectrum. Given the paucity of quiescent galaxies devoid of an interstellar medium at z \gtrsim 2, H I selection should yield galaxies spanning nearly the complete distribution at any redshift. Our ALMA [C II] 158\,\mu m sample of 19 DLAs therefore defines a representative set of normal, star-forming systems in their early phases of formation.

Our ALMA observations of two DLAs in an initial low-resolution [C II] 158\,\mu m search resulted in the discovery of strong [C II] 158\,\mu m emission from galaxies associated with the DLAs (Neeleman et al. 2017). In one of these galaxies, at z \approx 3.7975 toward DLA 1201+2117.3_80, the [C II] 158\,\mu m morphology and kinematics showed evidence for a complex system, which we suggested might arise from a pair of merging galaxies. Here, we present new ALMA observations, using a more extended configuration, aiming to resolve the [C II] 158\,\mu m and dust far-infrared (FIR) continuum emission.

This Letter is organized as follows. Section 2 presents the new ALMA observations, while Section 3 characterizes the morphology of the merging galaxies, and discusses the implications for estimating f_{\text{MM}}^2 at z > 2. We conclude in Section 4 with thoughts on the future and a brief summary. Throughout the Letter, we adopt a \Lambda-Cold Dark Matter cosmology with cosmological parameters as defined in Planck Collaboration et al. (2016), and report physical distances unless otherwise noted.

2. Observations and Data Analysis

The z = 3.7975 DLA toward J12010.31+211758.5 (hereafter DLA 1201+2117_3.80), with an H I column density of N_{HI} = 10^{21.35} \text{cm}^{-2}, was discovered by a DLA survey of the Sloan Digital Sky Survey (Prochaska et al. 2005). Follow-up Keck/ESI observations yielded a high gas-phase metallicity ([M/H] \approx -0.75) and a large velocity width \Delta v_{90} for its low-ionization metal-line profiles (Rafelski et al. 2012). Because of these features, we selected it for our original ALMA observations, which yielded detections of both [C II] 158\,\mu m line and dust-continuum emission from a galaxy offset by \pm 18 kpc from the quasar sight line at z = 3.7978 (Neeleman et al. 2017).

Owing to the kinematic complexity of the [C II] 158\,\mu m line emission already present in the low-resolution observations and its relatively high flux density, we used the ALMA Band 7 receivers to observe the z = 3.7978 galaxy in configuration C43-4, with a higher angular resolution (0\arcsec 33, i.e., \approx 2.3 kpc at z = 3.7978), in Cycle 5, for a total on-source time of 2.25 hr. We used four 1.875 GHz IF bands for the observations, one centered on the redshifted [C II] 158\,\mu m line frequency (at 396.127 GHz), with 3840 channels, and the other three at neighboring frequencies, each with 128 channels to sample the dust continuum of the galaxy.

The initial data analysis was carried out with the ALMA pipeline in the Common Astronomy Software Application (CASA) package; this included the removal of bad data (e.g., due to non-working antennas), and calibration of the flux density scale and the antenna-based complex gains and system bandpass. After this, the target source data were split into a separate measurement set, and a self-calibration procedure was carried out on the continuum data, in CASA, to more accurately measure the antenna-based gains. The self-calibration procedure involved a few rounds of imaging and phase-only self-calibration, followed by a couple of rounds of amplitude-and-phase self-calibration and imaging, until the gain solutions converged and no improvement was seen in the image on further self-calibration. The self-calibration used a “robust” scheme, with custom routines written in the CASA environment.

The final naturally weighted continuum image has an rms noise value of \approx 30\,\mu Jy\,B^{-1} and an angular resolution of 0\arcsec 36 \times 0\arcsec 31. The peak signal-to-noise ratio on the image improved from \approx 100 before self-calibration to \approx 330 after self-calibration, and the image rms noise improved by a factor of \approx 1.7, indicating a significant improvement due to the self-calibration process. The antenna-based gains derived from the above procedure were then applied to the line data. Finally, a spectral cube was made using the visibilities from the band centered on the redshifted [C II] 158\,\mu m frequency, using natural weighting. The spectral cube has an rms noise of 250\,\mu Jy\,B^{-1} per 50 km s^{-1} channel, and an angular resolution of 0\arcsec 37 \times 0\arcsec 31.

Figure 1 presents the zeroth and first moments of the [C II] 158\,\mu m emission, centered on the galaxy position as determined from the lower-resolution data (J120110.26+211756.2). The axes are labeled in physical units (kpc), at z = 3.7978, with \Delta X, the negative offset in R.A., and \Delta Y, the offset in dec., relative to J120110.26+211756.2. At the higher spatial resolution of the new observations, the source reported by Neeleman et al. (2017) separates into several components, in both space and velocity. This is clearly visible in the [C II] 158\,\mu m channel maps (relative to z = 3.7978) shown in Figure 2, which further discriminate between the different components. At velocities \delta v < -50 km s^{-1}, the emission is dominated by an extended source located \approx 3 kpc east of J120110.26+211756.2. We refer to this source as component B, and note that it also exhibits substantial emission at \delta v > 0 km s^{-1}. At \delta v > 50 km s^{-1}, the brightest emission occurs at \Delta X \approx +1 kpc and \Delta Y \approx +3 kpc, which we refer to as component A. In between these two components is emission that spans a range of velocities, hereafter component C. For quantitative measurements, we define the following three regions, to clearly separate the three components:

1. A: emission below the line \Delta Y = -1.0 \Delta X + 1.0 kpc.
2. B: emission above the line \Delta Y = -1.0 \Delta X - 2.0 kpc.
3. C: emission between the above two lines.

These three components are labeled in Figure 1. The brightest components (A and B) are also clearly detected as separate dust peaks in the continuum emission map, whereas component C is observed as weak extended emission in the dust continuum (Figure 3). This suggests a scenario of two merging, star-forming galaxies (A and B), with stripped gas dominating the emission in component C. The lines demarcating the different components are shown in Figure 4.

To test the assertion of multiple sources, we attempted to fit the line emission with a single rotating-disk model using the
Figure 1. (Left) The zeroth-moment image showing the integrated [C II] 158 μm flux density of the galaxies A and B associated with DLA 1201+2117_3.80, centered on J120110.26+211756.2 here. The axes are labeled in physical units (kpc) at z = 3.7978 and with ΔX, the negative offset in R.A., and ΔY, the offset in decl., relative to J120110.26+211756.2. The lowest contour corresponds to 3σ significance (0.18 Jy km s$^{-1}$ beam$^{-1}$), with the contours increasing by a factor of $2^{1/2}$. (right) The first-moment image showing the flux density-weighted velocity field, restricted to regions where the integrated flux density exceeds 2.5σ significance. There are two kinematically distinct components which we associate with a pair of merging galaxies, labeled A and B. There is additional emission between these components, referred to as component C (see the text).

Figure 2. Channel maps of the [C II] 158 μm emission from the gas associated with DLA 1201+2117_3.80, relative to the redshift z = 3.7978. We label these emitting components A, B, and C, as defined in the main text; these have distinct spatial and/or kinematic signatures. Units on the color bar are Jy Bm$^{-1}$. 
fitting code described in Neeleman et al. (2019c). The code compares the observed spectral cube to a cube generated from the model convolved with the instrument resolution. The best-fit parameters and uncertainties are then estimated through a Markov Chain Monte Carlo analysis of the parameter space. While the first-moment map shows a significant velocity shear across the system, the residuals of the models are significantly higher than the rms uncertainty of the data cube. In other words, we find that no single-disk model can reliably reproduce the observed [C II] 158 µm line emission.

We therefore conclude that the emission arises from at least two physically distinct galaxies with projected separation δR ≈ 6 kpc and a line-of-sight velocity separation of δv ≈ 200 km s⁻¹. Although we cannot strictly rule out a chance projection, the probability that the true separation δR greatly exceeds δR scales as the cube of the ratio of the separations. Thus, the probability that the true separation is >30 kpc is <1%. The presence of substantial [C II] 158 µm emission between the two galaxies (component C) is further evidence that the galaxies are physically nearby. Simulations of merging galaxies report a high probability for galaxies with such small separations to undergo a merger (e.g., Patton et al. 2000). We therefore conclude that the [C II] 158 µm emission data indicate that A and B are in the process of merging.

3. Discussion

Our discovery of a pair of merging H I-selected galaxies with ALMA offers a unique opportunity to examine the astrophysics of galaxy mergers in the young universe, and inspires a new assessment of the fraction of major mergers. We discuss each of these in turn.

3.1. The Nature of a z ~ 4 Merger

In the previous section, we argued that the [C II] 158 µm line emission associated with DLA 1201+2117.3.80 arises from a complex of merging galaxies. This is based on the morphology and kinematics seen in Figures 1–3. We now describe the properties of these components to provide a quantitative assessment of the system that may be compared against models of galaxy mergers. Table 1 lists integrated and flux-weighted measurements for the line and continuum emission of the components. For these measurements, we have analyzed our naturally weighted data cube, using simple box-car integrations to estimate the integrated flux densities. We have converted the continuum flux density measurements (obtained at ν_{\text{rest}} ≈ 1.909 × 10^{12} Hz) to an IR luminosity (spanning 8–1000 microns) assuming the dust emits as a modified blackbody with T = 35 K and a Raleigh-Jeans slope of β = 1.6. For a discussion of the uncertainties of these assumptions for this galaxy see Neeleman et al. (2017).

From the measurements in Table 1, we estimate the C^+ /IR luminosity ratio \( L_{C^+}/L_{IR} \), which has been observed to anticorrelate with the IR surface density \( \Sigma_{\text{IR}} \). Smith et al. (2017); Litke et al. (2019) yielding a [C II] 158 µm deficit in the most intensely star-forming regions. The \( L_{C^+}/L_{IR} \) values for components A and B are consistent with the values derived from z > 2 galaxies with modest SFRs (e.g., Capak et al. 2015). This supports the association of these components with individual, normal galaxies.

The integrated flux of central component C, however, shows a much higher \( L_{C^+}/L_{IR} \) ratio: a factor of approximately two times higher than the integrated values for the other two components. This is illustrated in Figure 4 and Table 1. Referring to Figure 1, the [C II] 158 µm emission in this region is not substantially higher than that from components A or B; the high \( L_{C^+}/L_{IR} \) ratio here is thus driven by low dust-continuum emission (Figure 3) and therefore a low \( L_{IR} \) value. Indeed, the ratio in component C lies close to an extrapolation.
of the relation between $L_{C^2}/L_{IR}$ and $\Sigma_{IR}$ to lower $\Sigma_{IR}$ values (see also Smith et al. 2017). This would imply either a dust-poor environment or, less likely, dust with a substantially lower temperature. It further suggests that the [C II] 158 $\mu$m emission in component C does not mainly arise from photodissociation regions but instead tracks primarily atomic or even ionized gas.

Elevated [C II] 158 $\mu$m luminosities relative to the dust emission have been reported for Lyman-break galaxies at $z \sim 5$, possibly due to lower internal dust-to-gas ratios (e.g., Capak et al. 2015). The $z = 3.7978$ galaxy, however, marks the first report of spatial variations within a system to such high $L_{C^2}/L_{IR}$ values. We propose that the gas in component C is material stripped from one (or both) of galaxies A and B. This leads to the picture of two merging, star-forming galaxies that have tidally interacted to pull gas into the region between them. This picture is supported by theoretical results on merging galaxies that predict significant tidal interactions when galaxies lie within $\lesssim 10$ kpc (Chilingarian et al. 2010), although a quantitative comparison is beyond the scope of this Letter.

It is commonly assumed that merger events drive an enhanced SFR in gas-rich galaxies. This assertion has theoretical underpinnings (Mihos & Hernquist 1996) and observational support, e.g., the frequent detection of multiple components in the most luminous submillimeter galaxies (Hayward et al. 2018). However, as noted above, components A and B have modest $L_{IR}$ values and correspondingly modest SFRs: (A) $\approx 10.8 \pm 1.5 M_{\odot}$ yr$^{-1}$ and (B) $\approx 7.8 \pm 1 M_{\odot}$ yr$^{-1}$. These values are consistent with the local correlation between SFR and [C II] 158 $\mu$m line luminosity (De Looze et al. 2011, 2014). We thus find no evidence for elevated star formation in this merger. Given that it was selected in absorption, we speculate that the elevated SFRs reported for other mergers may represent a selection bias.

### Table 1: Measurements

| Quantity | Unit | Value$_A$ | Error$_A$ | Value$_B$ | Error$_B$ | Value$_C$ | Error$_C$ | Value$_D$ | Error$_D$ |
|----------|------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\int \Delta$C II d$\nu$ | Jy km s$^{-1}$ | 0.51 | 0.007 | 0.51 | 0.006 | 0.34 | 0.005 | 1.36 | 0.010 |
| $L_{C^2}$ | $10^4 L_{\odot}$ | 2.5 | 2.5 | 0.0 | 0.0 | 1.7 | 0.0 | 6.6 | 0.1 |
| $f_{IR}$ | mJy | 0.133 | 0.003 | 0.097 | 0.003 | 0.039 | 0.002 | 0.269 | 0.005 |
| $L_{IR}$ | $10^2 L_{\odot}$ | 10.0 | 7.2 | 0.2 | 0.2 | 2.9 | 0.2 | 20.1 | 0.4 |
| SFR | $M_{\odot}$ yr$^{-1}$ | 10.8 | 7.8 | 0.2 | 0.2 | 3.1 | 0.2 | 21.8 | 0.4 |
| $L_{C^2}/L_{IR}$ | $10^{-3}$ | 2.5 | 3.4 | 0.1 | 0.1 | 5.8 | 0.3 | 3.3 | 0.1 |
| $v$ | km s$^{-1}$ | 44.4 | N/A | 1.7 | N/A | 7.7 | N/A | 19.3 | N/A |

Notes. Note that fluxes and quantities derived from them (e.g., SFR) have a systematic error of 15%.

- $^a$ Component A, defined relative to J120110.26+211756.2 as the gas below the line decl.$_{\text{off}}$ = $-1.0R.A._{\text{off}}$ $+$ 1.0 kpc.
- $^b$ Component B, defined relative to J120110.26+211756.2 as the gas above the line decl.$_{\text{off}}$ = $-1.0R.A._{\text{off}}$ $+$ 1.0 kpc.
- $^c$ Component C, defined as the gas between the lines defining A and B.
- $^d$ Total.
- $^e$ IR luminosity for $\lambda = 8$–1000 microns, estimated from the continuum flux assuming a modified blackbody with $T = 35$ K.

### Figure 5

Comparison of the kinematic profiles (relative to $z = 3.7975$) of the DLA absorption (black), the FeII 1608 profile with the [C II] 158 $\mu$m emission of galaxies A–C (blue, red, green) and the total, flux-weighted profile (gray).

The galaxy emission kinematics are consistent with two of the three main complexes of the DLA, and one is motivated to invoke a causal connection, i.e., that the galaxy merger yields the large $\Delta v_{90}$ of the DLA.

complexes of the absorption profile. The only (possible) exception is the absorption at $\Delta v < -200$ km s$^{-1}$, which corresponds to $\approx 20\%$ of the total optical depth.

The close correspondence in kinematics between the galaxy’s [C II] 158 $\mu$m emission and the metal-line absorption suggests a causal relationship, i.e., that gas associated with the merging galaxies contributes to the DLA profile to yield its high $\Delta v_{90}$. Indeed, a number of previous studies on DLA kinematics have asserted that the largest values of the $\Delta v_{90}$ distribution $f(\Delta v_{90})$ correspond to DLAs arising from multiple, merging galaxies (e.g., Prochaska & Wolfe 1997; Maller et al. 2001; Pontzen et al. 2008; Bird et al. 2015).

Figure 6 shows the $f(\Delta v_{90})$ distributions measured from high-resolution absorption studies of DLAs, and is restricted to systems without kinematic preselection (Rafelski et al. 2012; Neeleman et al. 2013). The median of each $f(\Delta v_{90})$ distribution lies at $\approx 80$ km s$^{-1}$, which is predicted to reflect the gravitational potential of the dark matter halos hosting DLAs (Bird et al. 2015; Pérez-Rafols et al. 2018). One notes further that the $f(\Delta v_{90})$ distribution is highly asymmetric, i.e.,

$$f(\Delta v_{90}) = \frac{1}{\sqrt{2\pi \sigma}} \exp \left( -\frac{(\Delta v_{90} - \mu)^2}{2\sigma^2} \right)$$

where $\mu$ is the median of the distribution, and $\sigma$ is the standard deviation.

The distribution is skewed to the left, indicating that the majority of DLAs have $\Delta v_{90}$ values below the median, consistent with the interpretation that these absorbers are part of the infalling gas clouds that will eventually be incorporated into the galaxy itself.

3.2. On the Origin of High $\Delta v_{90}$ DLAs

Figure 5 compares the line-of-sight velocity profiles of the three [C II] 158 $\mu$m components with a low-ionization metal-line absorption profile, each relative to $z = 3.7975$. The velocity width of the metal-line absorption is extreme, $\Delta v_{D,\text{DLA}} \approx 470$ km s$^{-1}$, which we again emphasize was part of our selection criteria for the original ALMA search for [C II] 158 $\mu$m emission (Neeleman et al. 2017). Tellingly, the velocity profiles of the three [C II] 158 $\mu$m components span nearly the entire velocity width of DLA 1201+2117.3.80. Specifically, these components correspond closely to the main

$$\Delta v_{90} = \mu + \frac{3\sigma}{2}$$

where $\mu$ is the median of the distribution, and $\sigma$ is the standard deviation.
skewed with a tail to high $\Delta v_{90}$ values. The 90th percentile of the $z \sim 2$ and $z \sim 4$ distributions are $\approx 200$ km s$^{-1}$ and $\approx 260$ km s$^{-1}$, respectively. These exceed the differential velocity that can be produced by a rotating disk, even with extreme thickness, inclination, and rotation speed (Prochaska & Wolfe 1997). This has motivated interpretations involving multiple galaxies and mergers, to account for the high $\Delta v_{90}$ values (and the occasional call for nongravitational motions, e.g., winds; Nulsen et al. 1998).

While DLA 1201$+2117_{-3.80}$ offers only a single example, the results described here support the merger interpretation for DLAs with the highest $\Delta v_{90}$ values. Evidence for companion galaxies at the DLA redshift was also obtained by Neelam et al. (2019a) in another of our [C II] 158 $\mu$m emitters, at $z \approx 4.224$ toward PSS 1443$+2741$, albeit with a slightly larger separation, $\approx 12$ kpc. This absorber too has a large $\Delta v_{90}$ value, $\approx 284$ km s$^{-1}$ (Neelam et al. 2019a). Adopting this interpretation, it provides an explanation for why high-$\Delta v_{90}$ DLAs show a larger dispersion around the correlation between metallicity and DLA kinematics (Prochaska et al. 2008). It also tempers the need to introduce galactic-scale winds that accelerate neutral gas to speeds greatly exceeding the escape velocity.

\section{3.3. Inferring the Major Merger Fraction}

Having associated large $\Delta v_{90}$ values from DLAs with galaxy mergers, we proceed to use DLA statistics to roughly infer the (major) merger fraction of galaxies at $z > 2$. We make the ansatz that every DLA with $\Delta v_{90} > \Delta v_{90}^{\text{max}}$ tags an ongoing major merger. The ratio of the number of DLAs with $\Delta v_{90} > \Delta v_{90}^{\text{max}}$ to the total number of DLAs then immediately yields the fraction of DLAs undergoing a merger.

$$f_M^{\text{DLA}} = \frac{\int_{\Delta v_{90}^{\text{max}}}^{\infty} f(\Delta v_{90}) \, d\Delta v_{90}}{\int_0^{\infty} f(\Delta v_{90}) \, d\Delta v_{90}}.$$ \hspace{1cm} (1)

Taking $\Delta v_{90}^{\text{max}} = 150$ km s$^{-1}$, as inferred from the $f(\Delta v_{90})$ distributions in Figure 6, we estimate $f_M^{\text{DLA}} = 0.14$ and 0.18 for $z \sim 2$ and 4, respectively. Given that there would not be a sharp transition in $\Delta v_{90}^{\text{max}}$ on the occurrence of a merger, we allow $\Delta v_{90}^{\text{max}}$ to range from 125 to 200 km s$^{-1}$, and thus estimate the systematic uncertainty on these $f_M^{\text{DLA}}$ estimates.

Orientation and projection effects may yield $\Delta v_{90} = \Delta v_{90}^{\text{max}}$ for some mergers; one might hence adopt these $f_M^{\text{DLA}}$ values as lower limits to the DLA merger fraction. Conversely, it is possible that other physical processes contribute to large $\Delta v_{90}$ values, implying that the $f_M^{\text{DLA}}$ values are overestimates. This could include minor mergers, although numerical simulations suggest that their contributions are small (Bird et al. 2015). We proceed with our nominal approach and emphasize that this yields only a coarse estimate of the major merger fraction. Analysis of simulations could constrain these effects; however, this is beyond the scope of this Letter.

To roughly estimate the merger fraction of galaxies, one must account for the cross-sectional weighting that is inherent to DLA analysis, i.e., systems with a larger projected area $A_{\text{DLA}}$ whose H I column density exceeds the DLA threshold have a higher probability of intersecting a quasar sight line. If the merger does not affect $A_{\text{DLA}}$, then we expect the merging system to have $A_{\text{merger}} = 2A_{\text{DLA}}$, i.e., twice the area owing to the presence of two galaxies. This leads to an estimate for the fraction of galaxies undergoing a major merger: $f_M^{\text{merger}} = f_M^{\text{DLA}} / (2A_{\text{DLA}} / A_{\text{merger}})$. Any enhancement due to the merger, e.g., from stripped gas as inferred for the system presented here, would require a downward correction. In the following, we include a systematic uncertainty to $f_M^{\text{merger}}$ corresponding to allowing $A_{\text{merger}}$ to range from 2 to 4 $A_{\text{DLA}}$.

Figure 7 presents our first estimates of $f_M^{\text{merger}}$ from DLA surveys (blue). These are presented as error intervals that express the large systematic uncertainties described above. They are compared with estimates of $f_M^{\text{merger}}$ from the incidence of spectroscopically confirmed galaxies with $\delta R < 25$ kpc and $\delta v < 500$ km s$^{-1}$ (green; Ventou et al. 2017). It is clear that our results are consistent with the directly observed merger fraction (Ventou et al. 2019), albeit with large systematic uncertainties.
We do not observe the decrease in $f_{\text{MM}}^3$ at higher redshifts, although our large systematics do not allow us to constrain the evolution with redshift.

4. Summary

We have used the ALMA Band 7 receivers to image, at $\approx 2 \text{kpc}$ resolution, the [C II] 158 \(\mu\text{m}\) line and FIR dust-continuum emission from an absorption-selected galaxy at $z = 3.7978$. The [C II] 158 \(\mu\text{m}\) and dust emission arise from at least three distinct source components lying within $\approx 10 \text{kpc}$ (projected), two of which (components A and B) have $L_{\text{CII}}/L_{\text{IR}}$ ratios consistent with values in high-$z$ galaxies with moderate SFRs, while the third (component C) has an elevated $L_{\text{CII}}/L_{\text{IR}}$ ratio. The images are consistent with a scenario in which components A and B are normal star-forming galaxies separated by $\approx 6 \text{kpc}$ and undergoing a major merger, while component C arises from gas that has been stripped from one or both of the galaxies. The velocity spread of the [C II] arises from gas that has been stripped from one or both of the galaxies. We propose that major mergers at high redshifts can be identified in DLAs. We have used the ALMA Band 7 receivers to image, at $90 \mu\text{m}$ resolution, the [C II] line in two of which are likely to have caused the large $\Delta v_{90}$ value of the DLA.

This is the first clear evidence that some of the large $\Delta v_{90}$ values observed in DLAs at $z > 3$ to roughly estimate the fraction of major mergers among normal high-$z$ galaxies $f_{\text{MM}}^3$, obtaining $f_{\text{MM}}^3 \approx 0.1$ at $z \approx 2.5$ and $z \approx 4$, consistent with independent estimates from recent VLT/MUSE studies (albeit with large systematic uncertainty).

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