A merger in the dusty, $z = 7.5$ galaxy A1689-zD1?

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ABSTRACT

The gravitationally-lensed galaxy A1689-zD1 is one of the most distant spectroscopically confirmed sources ($z > 7.5$). It is the earliest known galaxy where the interstellar medium (ISM) has been detected; dust emission was detected with the Atacama Large Millimetre Array (ALMA). A1689-zD1 is also unusual among high-redshift dust emitters as it is a sub-L* galaxy and is therefore a good prospect for the detection of gaseous ISM at this redshift. We observed A1689-zD1 with ALMA in bands 6 and 7 and with the Green Bank Telescope (GBT) in band $Q$. To study the structure of A1689-zD1, we map the mm thermal dust emission and find two spatial components with sizes about 0.4 – 1.7 kpc (lensing-corrected). The rough spatial morphology is similar to what is observed in the near-infrared with HST and points to a perturbed dynamical state, perhaps indicative of a major merger or a disc in early formation. The ALMA photometry is used to constrain the far-infrared spectral energy distribution, yielding a dust temperature ($T_{\text{dust}} \sim 35–45$ K for $\beta = 1.5–2$). We do not detect the CO(3-2) line in the GBT data with a 95% upper limit of 0.3 mJy observed. We find a slight excess emission in ALMA band 6 at 220.9 GHz. If this excess is real, it is likely due to emission from the [CII] line at $603.7$ µm. The stringent upper limits on the [CII] $L_{\text{dust}}/L_{\text{FIR}}$ luminosity ratio suggest a [CII] deficit similar to several bright quasars and massive starbursts.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: formation – submillimetre: galaxies

1 INTRODUCTION

With the increasing number of galaxies with spectroscopically confirmed redshifts $z > 7$ (Vanzella et al. 2011; Ono et al. 2012; Schenker et al. 2012; Shibuya et al. 2012; Finkelstein et al. 2013; Oesch et al. 2015; Watson et al. 2015; Zitrin et al. 2015; Song et al. 2016), the possibilities for quantifying and understanding the processes that take place during the earlier stages of galaxy formation and evolution improve significantly. Spectroscopic redshifts are necessary not only for determining the distance, but also for enabling detailed follow-up observations. For the $z > 6$ range, multiwavelength studies of quasars and submillimetre galaxies have been very successful (e.g. Maiolino et al. 2005; Venemans et al. 2012; Riechers et al. 2013; Wang et al. 2013; Willott et al. 2015a; Bañados et al. 2015; Cicone et al. 2015; Venemans et al. 2016), however those sources represent the very bright end of the luminosity function, and they are not representative of the overall galaxy population.

Recent searches for dust and far-infrared emission lines towards $z \sim 7$ galaxies have resulted in only a few line detections (e.g. Kanekar et al. 2013; Ouchi et al. 2013; González-López et al. 2014; Ota et al. 2014; Maiolino et al. 2015; Schaerer et al. 2015; Willott et al. 2015b; Knudsen et al. 2016; Pentericci et al. 2016; Bradač et al. 2016). These galaxies have non-detections or marginal detections in the far-infrared continuum suggesting that the dust-mass is relatively low. However, Watson et al. (2015) found a clear detection of dust emission towards the spectroscopically confirmed $z = 7.5$ galaxy Abell 1689-zD1 (A1689-zD1; Bradley et al. 2008) with an estimated dust mass comparable to that of the Milky Way. A1689-zD1 is strongly lensed by a factor of 9.3, thus providing constraints on a sub-$L^*$ galaxy (sub-$L^*$ for $z \sim 7.5$). The estimated stellar mass is $\sim 1.7 \times 10^{9} M_{\odot}$, and a total star formation rate (SFR) of $\sim 12 M_{\odot}$ yr$^{-1}$, which is dominated by dust-obscured star formation.
formation (Watson et al. 2015). Given the relatively short time after the big bang, it is unclear what mechanisms have produced such a large dust mass in this galaxy (e.g. Michalowski 2015).

In this paper we present a follow-up study of A1689-zD1 aimed at a detailed investigation of the structure of the dust emission and thus the distribution of obscured star formation. Furthermore, we report observations of emission lines from [C ii] 1900.537 GHz and CO(3-2) in order to study the properties of the interstellar medium (ISM) and accurately measure the systemic redshift. In Section 2, we present Atacama Large Millimetre Array (ALMA) and Green Bank Telescope (GBT) observations. In Section 3 we show the results of the observations and place it in the context of previous observations. We discuss the implications of the results in Section 4. Throughout the paper we assume a ΛCDM cosmology with $H_0 = 67.3\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_M = 0.315$, and $\Omega_{\Lambda} = 0.685$ (Planck Collaboration XVI 2014).

2 OBSERVATIONS

2.1 ALMA observations

A1689-zD1 was observed with ALMA during Cycle-2 with the observations carried out during December 2014 using band 6, and May 2015 and April 2016 with band 7. The purpose of the band-6 observations was to search for the redshifted [C ii] line and, as the optical redshift is determined from the Lyman-α break and not from emission lines (Watson et al. 2015), we designed the observations to cover a large frequency range. The receiver was tuned with three different setups, each with three spectral windows in one side band, which enabled continuous coverage from 216.51 to 231.06 GHz corresponding to the redshift range $z = 7.225 - 7.778$ for [C ii] $^1$. The band 7 receiver was tuned to 343.5 GHz for continuum measurements. The telescope configuration has baselines extending between 15 and 348 m. Table 1 summarizes the details of the observations including a list of the calibrators.

CASA (common astronomy software application) 2; McMullin et al. (2007) was used for reduction, calibration, and imaging. The results from the pipeline reduction 3 carried out by the observatory was generally sufficient with only some minor extra flagging, which did not change the final result. Exception to this was the flux calibration of the final band-7 observations, for which the flux calibration had to be adjusted with updated flux density values for the calibrator J1256–0547 (a.k.a. 3C279). This update corresponded to about 10%. We note that according to the ALMA calibrator source catalogue 4, 3C279 was variable up to 30% in the month before our observations in 2016, though in April 2016 it appears to have been more stable. While individual fluxes for 3C279 have ~5% errors, we place a conservative flux calibration uncertainty of 10% for our band-6 results. Continuum maps were made for both the band-6 and band-7 data. Using natural weighting, the obtained rms is $21\,\mu\text{Jy beam}^{-1}$ and $45\,\mu\text{Jy beam}^{-1}$, respectively. Additionally, a spectral cube was created for the band 6 data, and with natural weighting in channels of 26 km s$^{-1}$ width, the rms is ~0.5 – 0.8 mJy beam$^{-1}$ channel$^{-1}$ (typically the highest noise is towards the highest frequency across the spectrum).

Similar to our description in Watson et al. (2015), the most conservative estimate of the astrometric uncertainty is half the beam dimensions, meaning ~0.65 arcsec $\pm$0.34 arcsec. There is no notable emission detected from the nearby, low-$z$ galaxy seen 1.5 arcsec from A1689-zD1. We report the serendipitous detection of a background source in the band 6 data in a forthcoming paper (Knudsen et al., in preparation).

2.2 GBT observations

The GBT was used to search for the redshifted CO(3-2) line ($\nu_{\text{rest}} = 345.796$ GHz). The dual-beam Q-band receiver was tuned to a central frequency of 40.265 GHz covering the frequency range of 38.710–42.65 GHz, which corresponds to $z_{\text{CO(3-2)}} = 7.11 – 7.93$. Five observing sessions were carried out between 2014-09-18 and 2014-10-30. Observing scans were taken with the ‘SubBeamNod’ mode which used the subreflector to switch between the two beams every 6 s. We observed the bright nearby quasar 3C279 every 50–60 min to point and focus the telescope and to monitor the gain of the system.

We used the new GBT spectrometer VEGAS for the spectral-line observations. Four overlapping spectrometers (VEGAS module 1) were used to cover the bandwidth for each beam and for both circular polarizations with a raw channel resolution of 1.465 MHz. Gbtdl was used to carry out the data reduction and calibration. The data have been corrected for the atmosphere and losses due to drifts in pointing and focus during the observations. Observations of 3C286 were used to derive the absolute calibration scale of the data. The uncertainty on the flux scale for the data is estimated to be 15%. For a channel resolution of 1.465 MHz, we achieved 1σ rms of 0.267 mJy, and smoothed to 8.79 MHz (6 channels) the measured rms is 0.14 mJy; 8.79 MHz corresponds to 65 km s$^{-1}$ for $\nu = 40.6$ GHz.

3 RESULTS

3.1 Continuum

A1689-zD1 is detected in both bands 6 and 7 in continuum at $>10\sigma$. The emission is resolved with the structure showing two components. In Fig. 1 we show the bands 6 and 7 contours overlaid on an HST near-infrared image. Using the program PMM (Martí-Vidal et al. 2014) assuming a circular 2D Gaussian, we fit both bands together and measure a diameter (FWHM) of 0.52 $\pm$ 0.12 arcsec and 0.62 $\pm$ 0.12 arcsec for the two components (NE and SW, respectively); in the fit we have allowed for an astrometric offset between the two bands and find an insignificant offset in right ascension of 0.008 $\pm$ 0.108 arcsec, while in declination the offset is 0.166 $\pm$ 0.065 arcsec. Within the uncertainties, the two components have the same size. We note that fitting an elliptical 2D Gaussian function does not improve the results and the estimated major–minor axis ratio is consistent with one within the estimated uncertainties. Lensing magnification 5 is estimated to be $1.5 \times 6.5$ with the axis of the largest magnification roughly along a position angle

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1 This frequency range was selected based on the original error range to a simple fit to the Lyman-α break in the X-Shooter spectrum. However, a more conservative estimate of the uncertainty based on multiple methods gives a somewhat larger range and is quoted in Watson et al. (2015).

2 https://casa.nrao.edu

3 For details on the pipeline, see https://almascience.eso.org/documents-and-tools/

4 almascience.eso.org/sc/

5 The estimates of the lensing magnification are based on an updated mass model of Abell 1689 (Limosin et al. 2007, Richard et al. in preparation).
Table 1. Summary of the ALMA observations, project 2013.1.01064.S. Columns are: ALMA band number, date of observations, number of antennas ($N_{ant}$), two columns of calibrators used for each set of observations, and the central frequency of each spectral window except for the continuum observations where we give the central frequency of the continuum band.

| Date (DD-MM-YYYY) | $N_{ant}$ | Calibrators | Flux | Bandpass + Gain | $\nu_{spw,central}$ (GHz) |
|-------------------|-----------|-------------|------|-----------------|--------------------------|
| Band 6 08-12-2014 | 35        | Ganymede    | J1256–0547 | 217.455, 219.036, 220.456 |
| 08-12-2014        | 35        | Ganymede    | J1256–0547 | 222.306, 223.806, 225.306 |
| 08-12-2014        | 35        | Titan       | J1256–0547 | 227.156, 228.606, 230.156 |
| Band 7 05-05-2015 | 34        | J1256–0547  | J1256–0547 | 343.5 (continuum) |
| 11-04-2016        | 42        | J1256–0547  | J1256–0547 | 343.5 (continuum) |

90 degrees, which implies that the smallest scale in that direction is about 0.4 kpc. This could indicate that the two clumps are somewhat elongated (0.41–0.49 kpc by 1.8–2.1 kpc with an uncertainty of about 50%) as also seen in the lensing reconstruction of Bradley et al. (2008), however, the ALMA data does not have sufficient quality to further reaffirm this. The estimated area for both clumps together is $\sim 1$ kpc$^2$, consistent with the estimate based on the HST near-infrared data (Watson et al. 2015).

From the $\nu_{spw,central}$ results we also obtain an estimate of the flux density of $f_{\nu_\star} = 1.33 \pm 0.14$ mJy (the sum of 0.58 $\pm$ 0.09 and 0.75 $\pm$ 0.11 mJy, for NE and SW respectively) and $f_{\nu_{spw}} = 0.56 \pm 0.1$ mJy (sum of 0.20 $\pm$ 0.08 and 0.36 $\pm$ 0.06 mJy for NE and SW respectively). The errors reflect the uncertainties of the flux estimate and the errors on the total flux density are obtained from adding the individual errors in quadrature.

We use the photometric data points to constrain the far-infrared spectral energy distribution (SED). The observed frequencies correspond to rest-frame wavelengths of 157.6 $\mu$m and 102.7 $\mu$m, respectively, for $z = 7.5$. This means we are probing close to the peak of the dust emission. In Fig. 2 we show the measured fluxes together with the rest of the SED as presented in Watson et al. (2015). We constrain the temperature of a modified blackbody spectrum using the ratio of the fluxes from bands 7 and 6, where the modified blackbody function is described as $\nu^\beta B_\nu(T)$. For $z = 7.5$ the cosmic microwave background (CMB) temperature is $\sim 23$ K. We estimate that the CMB would increase the temperature by $\sim 1$ per cent and that $5 - 23$ per cent of the intrinsic flux is missed due to the CMB radiation depending on the dust temperature, following the analysis of da Cunha et al. (2013). When estimating the dust temperature of A1689-zD1, we take the missed flux into account, but ignore the small change in temperature. In Fig. 3 we show how an estimated flux ratio changes with temperature for three different $\beta$-values and compare this to our measured flux ratio of $f_{\text{band-7}}/f_{\text{band-6}} \sim 2.4$. We find the best-fitting values of $T = 46.5$, 40.5, and 35.8 K for $\beta = 1.5, 1.75, 2.0$, respectively. When not taking into account the effects of the CMB, the temperature estimates would be about 5 K higher. For $T = 40.5$ K and $\beta = 1.75$ the far-infrared luminosity is $1.7 \times 10^{12}$ L$_\odot$ (1.8 $\times 10^{11}$ L$_\odot$ after correcting for magnification); we note that the fraction of missed flux is $\sim 8$ and $\sim 16$ per cent for bands 7 and 6, respectively. Using the two other estimates for $\beta = 1.5$ and 2.0, the luminosity would increase/decrease by about 20 per cent. Given the uncertainties, this is in agreement with the estimate and assumptions made in Watson et al. (2015).

We update the MAGPHYS (da Cunha et al. 2008) and grasil with the calculations done using lenstool. (Jullo et al. 2007; Jullo & Kneib 2009). (Silva et al. 1998; Iglesias-Páramo et al. 2007; Michalowski et al. 2010) SED model fits from Watson et al. (2015) using the new ALMA band 6 + 7 photometry including the same correction for CMB effects as described in the previous paragraphs. We find the derived parameters to be SFR = $12.4^{+6.2}_{-4.4}$ M$_\odot$ yr$^{-1}$, log(M$_{\text{dust}}$/M$_\odot$) = $9.3^{+0.6}_{-0.5}$, and log(M$_{\text{dust}}$/M$_\odot$) = $7.6^{+0.7}_{-0.6}$ from MAGPHYS, and SFR = $14 \pm 8$ M$_\odot$ yr$^{-1}$, log(M$_{\text{dust}}$/M$_\odot$) = $9.4 \pm 0.1$, and log(M$_{\text{dust}}$/M$_\odot$) = 7.2 $\pm$ 0.2 from grasil. The new and deeper ALMA measurements, provides a better constraint on the far-infrared SED, e.g. for the dust temperature. The largest change in the derived parameters compared to Watson et al. (2015) is the lower nominal dust mass from the grasil fit, though this is consistent within the uncertainties. We plot the updated SED models in Fig. 2 and note that while the models are quite similar, the largest difference is found on the Wien’s tail and mid-infrared range. That is a wavelength range which is difficult to cover with present instrumentation, however, part of it can be studied soon with the James Webb Space Telescope.
show 3σ sources in the imaging, however, with a lower spatial overlap. If the spectral feature at 220.903 GHz is indeed a weak detection of the [C II] line, fitting a Gaussian function implies a peak flux density of $S_{\text{peak}} = 0.77 \pm 0.20$ mJy beam$^{-1}$. FWHM line width of $\Delta V = 163 \pm 49$ km s$^{-1}$, and a velocity integrated intensity $I_{\text{CII}} = 0.126 \pm 0.050$ Jy km s$^{-1}$ (the error on the velocity integrated intensity is derived from regular error propagation of the Gaussian fit), and a redshift of $z_{\text{CII}} = 7.6031 \pm 0.0004$. We show the tentative line and the image of the integrated line in Fig. 5. Under the assumption that this is indeed a detection of [C II], this would correspond to a line luminosity of $L_{\text{CII}} \sim 1.7 \times 10^5 L_\odot$ ($1.8 \times 10^7 L_\odot$ after correcting for the lensing magnification of $\mu = 9.3$) using $L_{\text{CII}} = 1.04 \times 10^{-3} \Delta V I_{\text{CII}} v_{\text{obs}}$, where $\Delta V$ is the velocity integrated flux density, $D_L$ is the luminosity distance, and $v_{\text{obs}}$ is the observer-frame frequency (e.g. Solomon & Vanden Bout 2005; Carilli & Walter 2013). Given that this is only a possible detection, we use the line luminosity as an upper limit.

3.3 CO(3-2) line search

In the GBT spectrum we do not detect the CO(3-2) line; the spectrum is shown in Fig. 6. The redshift range covered by the spectrum is $z_{\text{CO32}} = 7.12 \sim 7.93$. We place a 3σ limit for the same linewidth as the tentative [C II] line. This corresponds to $I_{\text{CO32}} = 8.6 \times 10^6$ K km s$^{-1}$ pc$^2$ ($9.0 \times 10^8$ K km s$^{-1}$ pc$^2$ after correcting for lensing) and $L_{\text{CO32}} = 1.1 \times 10^7 L_\odot$ ($1.1 \times 10^9 L_\odot$ after lensing correction).

Depending on the physical conditions of the gas, the CMB radiation field can significantly affect how well CO gas can be observed at very high redshifts. According to the estimates from da Cunha et al. (2013) for $z \sim 7.5$, the observed flux of CO(3-2) could be about half of the intrinsic flux if the density and temperature are high ($T \sim 40$ K, $n_H \sim 10^3$ cm$^{-3}$), and this ratio would be lower for lower temperature and densities. Thus the effect of the CMB could explain why we do not detect the CO(3-2). We note that cosmic ray destruction of CO has been suggested as mechanism to remove CO from the molecular gas (e.g. Bisbas et al. 2015).

Under the assumption that half of the intrinsic flux is missed due to the CMB radiation field and that the CO(3-2) is thermally excited, we estimate an upper limit on the molecular gas mass of $7.2 \times 10^4 M_\odot$, using a conversion factor $\alpha_{\text{CO}} = 4 M_\odot$ K km s$^{-1}$ pc$^{-2}$ (e.g. Carilli & Walter 2013). Given the large number of assumptions, this should be viewed as an order of magnitude estimate. Using the size estimate from the ALMA continuum observations, assuming a simple geometry, this would imply an average gas density $< 250$ cm$^{-3}$.

4 DISCUSSION

A1689-zD1 is currently unusual among $z > 7$ galaxies in that it is detected in thermal dust emission and has a spectroscopically-confirmed redshift without Ly$\alpha$ emission. The observations presented here also show that the galaxy is relatively small, with the galaxy resolved into two separate components, both in thermal dust emission and stellar continuum. Despite its relative modest size, the mean stellar surface density of about $1000 M_\odot$ pc$^{-2}$ is not exceptionally high, however, the SFR surface density of $\sim 7 M_\odot$ yr$^{-1}$ kpc$^{-2}$ as traced from the dust emission, is similar to that of starburst (e.g. Bouché et al. 2007); we note that the SFR surface density could be partly overestimated if the size estimate from the submm imaging has been underestimated because of the
contrast against the CMB [this effect is discussed in Zhang et al. (2016)]. Given the very high redshift of the galaxy, questions naturally arise over how the galaxy came to be dusty and have apparently high metallicity this early, its lack of strong UV and FIR emission lines, and its morphology.

### 4.1 Could A1689-zD1 be a merging galaxy pair?

In order to assess the possibility of A1689-zD1 being a merging galaxy pair, we estimate the descendant halo mass using the abundance matching technique, and use the results from $N$-body cosmological simulations to approximate the average merger rate. With a lensing-corrected UV luminosity of ~$1.8 \times 10^{10}$ $L_{\odot}$, the mean halo mass of A1689-zD1 is ~$10^{13}$ $M_{\odot}$ at $z = 7.5$ (with a virial radius ~11 kpc). Specifically, we use the relation by Schultz et al. (2014); see their Fig. 6. This estimate is uncertain by a factor of ~2, e.g. see Fig. 15 of Harikane et al. (2016). The cumulative number of halo mergers with a mass ratio larger than $\xi_{\text{min}}$, between redshifts $z_0$ and $z$ that a descendant halo of mass $M_0(z_0)$ has suffered is:

$$N_m(\xi_{\text{min}}, M_0, z_0, z) = \sum_{z_0} dz \int_{\xi_{\text{min}}}^{\xi} d\xi \frac{dN_m}{d\xi dz} \left\langle (M(z)), \xi, z \right\rangle$$

(1)

where $dN_m/d\xi/dz$ is the mean merger rate in units of mergers per halo per unit redshift per unit $\xi$, and $\langle M(z) \rangle$ is the mean halo mass assembly history. In order to compute equation 1, we take the results of Fakhouri et al. (2010) based on the statistics of the Millennium II simulation (specifically, their fitting formulae 1 and 2). Given the observed features of A1689-zD1, we assume a major merger with a mass ratio of at least $\xi_{\text{min}} = 0.3$. If we further take $z_0 = 7.5$ and $z = 15$ (the maximum redshift where the formulae can be trusted) in equation 1, we find that $N_m \sim 2.1$. This number is most sensitive to the initial redshift $z$, e.g. it drops by a factor of ~4 if $z = 9$ instead of $z = 15$. Albeit given the evolved nature of the galaxy, it likely formed its first stars earlier than $z \sim 10$, thus $N_m$ is likely larger than 0.5. We can then conclude that a merger under the conditions of A1689-zD1, should be a common occurrence according to our knowledge of structure formation. With such a mass ratio, and a descendant mass, a merger will occur in a time-scale (governed by dynamical friction) of $\mathcal{O}(100 \text{Myr})$ [Binney & Tremaine (1987); calibrated with the results of Boylan-Kolchin et al. (2008)]. This time-scale is defined from the time the virial radii of the two haloes started to overlap.

The clumpy structure of A1689-zD1 could possibly also be the result of gravitational instabilities if A1689-zD1 is a disc galaxy in formation. Modelling by Ceverino et al. (2010) shows that giant clumps can arise in a scenario where cold streams providing the gas can cause discs to be gravitationally unstable and turbulent. Signatures of clumps in disc galaxies and ‘proto-discs’ are found both in optical studies of high-$z$ spiral galaxies (e.g. Elmegreen et al. 2009a,b) and in molecular gas studies (e.g. Tacconi et al. 2010), where the latter finds clumps with masses $\sim 5 \times 10^7 M_{\odot}$ and intrinsic radii $<1-2$ kpc. We do not have the observational results to constrain whether A1689-zD1 is a merging galaxy pair or the result of cold mode accretion, however, the important point is that the structure we observe is similar in both the near-infrared (i.e. rest-frame UV) and thermal dust emission, indicative of a dynamically perturbed system.

In either case of interacting galaxies or clumpy structure arising from dynamical instabilities, the average density of the gas is increased and the SFR will increase. A1689-zD1 has a comparatively high SFR and dust continuum emission, and with a stellar mass of ~$10^9 M_{\odot}$ it is expected that the metallicity is not low. These conditions seem to make A1689-zD1 an interesting galaxy pair or the result of cold mode accretion, however, the important point is that the structure we observe is similar in both the near-infrared (i.e. rest-frame UV) and thermal dust emission, indicative of a dynamically perturbed system.
Shooter spectrum covered a wide wavelength range, both in the optical and near-infrared. As presented in Watson et al. (2015), the redshift is determined from a clear break around ~ 1 μm, though no lines were detected, resulting in an accuracy of σ_z ~ 0.2. One of the goals of the ALMA and GBT observations was to observe line emission in order to get an accurate measurement of the redshift. As mentioned previously, both the ALMA and GBT data provide a wide coverage for two lines that in lower redshift star-forming galaxies would be bright. We obtain a tentative 3σ detection of the [CII] line with a corresponding redshift of z_{[CII]} = 7.603, however, deeper observations are necessary to confirm this. It is possible that the systemic redshift of A1689-zD1 may not have been covered by the observations. Adopting σ_z ~ 0.2 as a 68% confidence interval, which is very conservative, this corresponds to a minimum 80% coverage of the probability interval for the [CII] line, and similarly a minimum 95% coverage for the CO(3-2) line. We will work in the next section on the assumption that we cover these emission lines in these observations. Equally, however, non-detections of these two lines could also be due to astrophysical reasons in A1689-zD1 it-self (see Sections 3.3 and 4.3, also see e.g. Maiolino et al. (2015) for an example of z > 7 galaxies with [CII] non-detections). We explore this possibility below.

4.3 [CII]/L_{FIR} deficit?

With the upper limit from the tentative detection of [CII] we find that the luminosity ratio is \( L_{[\text{CII}]} / L_{\text{FIR}} < 0.0002 \). This is low in comparison to local star-forming galaxies (e.g. Malhotra et al. 2001; Díaz-Santos et al. 2013), which typically have luminosity ratios of 0.0007–0.007 for galaxies with \( L_{\text{FIR}} < 10^{11} \text{L}_\odot \). In fact the limit is closer to the ratios typically obtained for massive, luminous starbursts found in some quasar host galaxies (e.g. Wang et al. 2013), indicating that A1689-zD1 is [CII] deficient. While the reasons for this deficit observed towards several massive starbursts remain unclear, a number of possible explanations have been suggested (e.g. Luhman et al. 2003; Stacey et al. 2010). For example, a high radiation field relative to the gas density could cause an increased far-infrared luminosity compared to several emission lines such as [CII] (e.g. Luhman et al. 2003; Abel et al. 2009). If the gas density exceeds the critical density of [CII], collisional de-excitation...
will become important and reduce the cooling by [C\text{n}] (e.g. Goldsmith et al. 2012). Alternatively, if the gas temperature exceeds the excitation temperature of the [C\text{n}] line, a saturation of the upper fine-structure level would occur, resulting in a maximum \( L_{\text{CII}} \) even at increasing \( L_{\text{IR}} \) (e.g. Muñoz & Oh 2016). A recent model from Narayanan & Krumholz (2016) suggests that the surface density plays an important role, i.e. an increase of the gas surface density would lower the total amount of C\text{i} and an increase of CO, which would result in a decreased \( L_{\text{CII}}/L_{\text{IR}} \) ratio.

In nearby, star-forming galaxies, [C\text{n}] has been found to be reliable tracer of the SFR (e.g. De Looze et al. 2014; Díaz-Santos et al. 2014). It has thus been expected that [C\text{n}] would be a bright tracer of the star formation taking place even in the highest-\( z \) galaxies, enabling discovery of sites of on-going (and obscured) star formation as well as enabling means to reliably measure SFRs. However, the non-detections of non-SMG and non-QSO star-forming galaxies have revealed a more complex picture of galaxy evolution during the first 0.5–1 Gyr after the big bang. In Fig. 7 we show the \( L_{\text{CII}}-\text{SFR} \) relation for \( z > 6 \) star-forming galaxies including A1689-zD1 in comparison with the relations derived from low-\( z \) galaxies.

The lack of [C\text{n}] detections towards a large number of \( z > 6 \) star-forming galaxies has been discussed to be the consequence of low metallicity (González-López et al. 2014; Ota et al. 2014; Capak et al. 2015; Maiolino et al. 2015; Schaerer et al. 2015; Willett et al. 2015b; Knudsen et al. 2016). Low metallicity could bring down the expected [C\text{n}] line luminosity. In fact modelling of the gas in \( z > 6 \) galaxies suggests that the local SFR-\( L_{\text{CII}} \) relation is decreased significantly depending on the metallicity (e.g. Vallini et al. 2015).

However, an explanation involving low metallicity in A1689-zD1 hard to reconcile with the high dust mass in this galaxy, a dust mass that suggests a metallicity close to the solar value (Watson et al. 2015). This makes the [C\text{n}] deficiency here perplexing, and instead seems to point to a powerful radiation field or high gas densities as the likely culprits in depressing [C\text{i}] emission. However, the measured SFR of \( \sim 12 \, \text{M}_\odot \, \text{yr}^{-1} \) is below the characteristic mean SFR for this galaxy of \( \sim 25 \, \text{M}_\odot \, \text{yr}^{-1} \) (as calculated from the stellar mass divided by the best-fitting age from the SED), and is not indicative of a galaxy at the peak of a massive starburst event. This suggests that a powerful radiation field is not the most obvious explanation for the [C\text{n}] deficiency. Our detection of a large dust mass clearly demonstrates that this galaxy must have a relatively high metallicity already.

5 CONCLUSIONS

In this paper, we present resolved observations of the dust continuum emission from A1689-zD1, which is presently the most distant known galaxy (\( z = 7.5 \pm 0.2 \)) with a detection of emission from thermal dust. Our findings are as follows:

- The deep band 6 and band 7 continuum observations show that the redshifted far-infrared emission is extended over two components, each of which has a FWHM size of \( \sim 0.45 \, \text{kpc} \times 1.9 \, \text{kpc} \) (after correcting for the gravitational lensing). We note that the combination of ALMA sub-arcsec observations with gravitational lensing provides an efficient approach to resolving the structure of the dust-emitting region. The gross far-infrared morphology is similar to the morphology of restframe UV light. This suggests that the galaxy is either two proto-galaxies interacting/merging or a clumpy protogalactic disc.

- Based on bands 6 and 7 ALMA photometry we derive a dust temperature \( T \sim 35 – 45 \, \text{K} \) (\( \beta = 1.5 – 2 \)) after correcting for the CMB radiation field. This implies a far-infrared luminosity of \( 1.8 \times 10^{11} \, \text{L}_\odot \) (corrected for lensing magnification), in agreement with our previous results based on single-band photometry.

- Based on deep ALMA band 6 spectroscopy with a 15 GHz coverage, the [C\text{n}] line is not detected. We present a tentative 3\( \sigma \) detection, which would imply a systemic redshift of 7.603. Using the derived line intensity and luminosity of the tentative line, we find that the line is underluminous relative to the far-infrared luminosity in comparison with local normal star-forming galaxies. Compared to the SFR, the upper limit is similar to the growing number of [C\text{n}] non-detections in \( z > 6 \) star-forming galaxies. While the non-detection can be explained astrophysically, we emphasize the possibility that a different redshift remains until a confirmed line-detection has been obtained.

- The CO(3-2) line is not detected in the GBT observations. Given the high temperature of the CMB radiation field at \( z \sim 7.5 \), it is difficult to determine an upper limit, however, we place an estimate on the limit of the molecular gas of \(< \sim 7 \times 10^5 \, \text{M}_\odot \) (assuming a Galactic \( L_{\text{CO}}-\text{to-M}_\text{H}_2 \) conversion).

Previous models for grain growth show that the time-scale is inversely proportional to the gas density. It is possible that the reported structure, indicative of galaxy interaction or clumps, could be the signature of increased gas density and thus accelerated grain growth. More importantly, the question remains whether the relatively large dust mass is special for A1689-zD1 or if future, deeper observations of large samples of galaxies will reveal a larger population of dusty, normal galaxies at \( z > 7 \).
APPENDIX A: MAPPING OF CANDIDATE EMISSION LINES

As described in Section 3.2, in order to search for the [C\textsc{ii}] line in the ALMA band 6 data, we imaged all the positive spectral features with flux > 0.6 mJy, which corresponds to ~ 2σ in the Hanning-smoothed spectrum. In this Appendix we show the maps constructed using a width of 0.1 GHz. In Fig. A1 we show the maps as contours overlaid on the near-infrared F160W HST image. A couple of the features show image contours of ~ 2.5σ around the position of A1689-zD1. The features of 220.903, 223.770, and 228.000 GHz show 3σ contours, however, only in the case of 220.903 GHz are they following the same position as the dust continuum. We note that this is possibly the best candidate line for redshifted [C\textsc{ii}] and therefore report it as a tentative detection.

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Figure A1. Images from integrating over 0.1 GHz at different frequencies. Red contours correspond to 2σ, 2.5σ, and 3σ, where σ is the r.m.s. measured in each image. The frequency is written in the upper-left corner of each sub-image and indicated with a green arrow on top of the spectrum shown in Fig. 4. As in Fig. 5, the black contours show the continuum image with natural weighting (5σ, 6σ, 7σ, 8σ, 9σ, and 10σ); the grey-scale image is the same as in Figs 1 and 5.

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