A solar metallicity galaxy at $z > 7$? Possible detection of the [N II] 122 μm and [O III] 52 μm lines

Killi, Meghana; Watson, Darach; Fujimoto, Seiji; Akins, Hollis; Knudsen, Kirsten; Richard, Johan; Harikane, Yuichi; Rigopoulou, Dimitra; Rizzo, Francesca; Ginolfi, Michele; Popping, Gergo; Kokorev, Vasilii

Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
10.1093/mnras/stad687

Publication date:
2023

Document version
Publisher's PDF, also known as Version of record

Document license:
CC BY

Citation for published version (APA):
A solar metallicity galaxy at z > 7? Possible detection of the [N II] 122 μm and [O III] 52 μm lines

Meghana Killi,¹ ² Darach Watson,¹ ² Seiji Fujimoto,¹ ² Hollis Akins,³ Kirsten Knudsen,⁴ Johan Richard,⁵ Yuichi Harikane,⁶ ⁷ Dimitra Rigopoulos,⁸ ⁹ Francesca Rizzo,¹ ² Michele Ginolfi,¹ ¹⁰ Gerg Popping¹¹ and Vasily Kokorev¹ ²

¹Cosmic Dawn Center (DAWN)
²Niels Bohr Institute, University of Copenhagen, Jagtvej 128, DK-2200 Copenhagen N, Denmark
³Department of Astronomy, The University of Texas at Austin, 2515 Speedway Blvd, Stop C1400, Austin, TX 78712, USA
⁴Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-43992 Onsala, Sweden
⁵Univ Lyon, Univ Lyon I, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon (CRAL) UMR5574, F-69230 Saint-Genis-Laval, France
⁶Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan
⁷Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
⁸Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
⁹School of Sciences, European University Cyprus, Diogenes Street, Engomi, 1516 Nicosia, Cyprus
¹⁰Dipartimento di Fisica e Astronomia, Università di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino (Firenze), Italy
¹¹European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany

Accepted 2023 February 25. Received 2023 February 25; in original form 2022 August 16

ABSTRACT

We present the first detection of the [N II] 122 μm and [O III] 52 μm lines for a reionization-epoch galaxy. Based on these lines and previous [C II] 158 μm and [O III] 88 μm measurements, using two different radiative transfer models of the interstellar medium, we estimate an upper limit on electron density of ≤500 cm⁻³ and an approximate gas-phase metallicity of Z/Z⊙ ∼ 1.1 ± 0.2 for A1689-zD1, a gravitationally lensed dusty galaxy at z = 7.133. Other measurements or indicators of metallicity so far in galaxy interstellar media at z > 6 are typically an order of magnitude lower than this. The unusually high metallicity makes A1689-zD1 inconsistent with the fundamental metallicity relation, although there is likely significant dust obscuration of the stellar mass, which may partly resolve the inconsistency. Given a solar metallicity, the dust-to-metals ratio is a factor of several lower than expected, hinting that galaxies beyond z > 7 may have lower dust formation efficiency. Finally, the inferred nitrogen enrichment compared to oxygen, on which the metallicity measurement depends, indicates that star formation in the system is older than about 250 Myr, pushing the beginnings of this galaxy to z > 10.

Key words: ISM: abundances – galaxies: high-redshift – galaxies: individual: (A1689-zD1) – galaxies: ISM – submillimetre: galaxies.

1 INTRODUCTION

The frontier of the study of galaxy evolution has now moved to the epoch of reionization, z > 7, where the physical conditions of the interstellar medium (ISM) are beginning to be investigated (e.g. Novak et al. 2019; Bouwens et al. 2022). Measuring these conditions is critical to our understanding of the evolution of galaxies and the growth of structure. The metal enrichment of the gas in galaxies, in particular, can tell us about the extent of processing of the ISM through stars, and therefore, the stage of evolution of the galaxy. However this fundamental ISM property is difficult to determine at high z.

While at low redshifts, ISM properties are often determined using optical and ultraviolet (UV) emission lines (e.g. Kewley, Nicholls & Sutherland 2019; Maiolino & Mannucci 2019), at z > 7 those lines shift into the infrared (IR), where JWST is just beginning to produce the first results (e.g. Schaerer et al. 2022; Curti et al. 2023). However, heavily dust-obscured galaxies (e.g. Marrone et al. 2018; Fudamoto et al. 2021) cannot be studied with JWST because UV–optical observations cannot probe dust-obscured gas (Chartab et al. 2022). Hence, at high redshift, we require detections of bright far-infrared (FIR) cooling lines and dust emission to estimate ISM properties (e.g. Nagao et al. 2011; Novak et al. 2019).

So far, FIR lines such as [C II] 158 μm and [O III] 88 μm (hereafter [C158] and [O88], respectively) have been detected in only a handful of z > 7 galaxies (e.g. Maiolino et al. 2015; Pentericci et al. 2016; Carniani et al. 2017, 2020; Hashimoto et al. 2019; Sommovigo et al. 2021; Schouws et al. 2022a). Very few galaxies have been detected in both [O88] and [C158] at z > 6 (Carniani et al. 2017; Hashimoto et al. 2019; Tamura et al. 2019; Bakx et al. 2020; Harikane et al. 2020; Wittok et al. 2022), and only four of those are at z > 7.

Furthermore, while observations of the [O88] and [C158] lines and continuum emission allow the star formation rate, dust mass, and, to some extent, the temperature to be assessed with some...
reliability, determining the basic ISM parameters, i.e. the gas-phase metallicity, density, and ionization parameter, requires other FIR lines. For instance, Pereira-Santaella et al. (2017) and Harikane et al. (2020) describe models that use lines such as [O II] 52 μm and [N II] 122 μm (hereafter [OII] and [NII], respectively) in addition to [OIII] and [CII].

However, this poses an observational challenge because while [OIII] and [CII] are bright, [NII] is relatively faint and difficult to detect at z > 6. There have been [NII] detections in quasar host galaxies at z = 6.003 (Li et al. 2020), and z = 7.54 (Novak et al. 2019), but non-detections for all other systems attempted at z ~ 6–7 (Harikane et al. 2020; Sugahara et al. 2021). Although the [OIII] line can be bright, it is also difficult to detect at this redshift as it lies in a wavelength region with low atmospheric transmission. Thus far, there have been no detections reported of [OIII] at z > 6.

In this work, we report on the first measurement of the [OIII] and [NII] lines for a non-quasar galaxy at z > 6. Together with previous [OIII] and [CII] measurements (Akins et al. 2022; Wong et al. 2022; Knudsen et al., in preparation), we now have four FIR line detections for the gravitationally lensed reionization-epoch, dusty, normal galaxy A1689-zD1 at z = 7.133, making it the ideal candidate to study ISM conditions in reionization era galaxies.

A1689-zD1 is lensed by the galaxy cluster Abell 1689 with a magnification factor of 9.3 (Watson et al. 2015). It was first discovered as a photometric candidate z > 7 galaxy (Bradley et al. 2008). The Lyα break was spectroscopically confirmed with deep Very Large Telescope (VLT)/X-shooter data, and it was shown to be a dusty galaxy with the Atacama Large Millimeter/submillimeter Array (ALMA) detections in bands 6 and 7 (Watson et al. 2015; Knudsen et al. 2017). This was the first detection of dust at z > 7, though more distant dust emitters have since been identified (e.g. Laporte et al. 2017; Fudamoto et al. 2021; Ferrara et al. 2022; Schouws et al. 2022b). A1689-zD1 has now been detected in strong [CII] and [OIII] emission (Wong et al. 2022), the detailed 2D and 3D structure of which is studied in Akins et al. (2022) and Knudsen et al. (in preparation). The galaxy has also been detected in four continuum bands allowing an accurate measurement of its dust temperature and mass (Bakx et al. 2021). The rich multiwavelength data set makes it one of the best-studied reionization-epoch galaxies.

In this paper, we report the measured line fluxes, and calculate ratios among the four lines and their underlying continua to characterize the ISM of A1689-zD1. We deal here mainly with the galaxy-integrated properties. A resolved study of A1689-zD1 is presented in Knudsen et al. (in preparation).

We adopt a flat Λ cold dark matter (ΛCDM) cosmology with H₀ = 67.74 km s⁻¹ Mpc⁻¹, ΩM = 0.3075, and ΩΛ = 0.6925 (Planck Collaboration XIII 2016).

2 OBSERVATIONS AND METHODS

For the analysis presented in this work, we use the following values for the stellar mass (M∗), dust mass (Md), and star formation rate (SFR) for the galaxy: M∗ = 1.7^{+0.5}_{-0.7} × 10^9 M⊙ (Watson et al. 2015); total SFR = 37 ± 1 M⊙ yr⁻¹ (Akins et al. 2022); and Md = 1.7^{+1.3}_{-0.7} × 10⁷ M⊙ (Bakx et al. 2021).

2.1 [NII] and [OIII] observations

Observations were carried out at the ALMA in Chile from 2019 November to 2019 December in cycle 7 (# 2019.1.01778.S, PI: D. Watson) under a precipitable water vapour (PWV) of 0.3–0.8 mm, using 42–45 antennas with projected baselines of 15–313 m. Based on a source redshift of z = 7.1332 ± 0.0005, securely determined with [CII] and [OIII] (Wong et al. 2022; Knudsen et al., in preparation), the available 7.5 GHz bandwidth with four spectral windows was centred at observed frequencies of 296.9 GHz (Band 7) and 703.8 GHz (Band 9) so that the [NII] and [OIII] lines fall within one or two spectral windows, J2129+0203 and J1337−1257 were observed as the flux and bandpass calibrators. Phase calibration was performed by using observations of J1256−0457. The total on-source times were 200 and 95 min for the [OIII] and [NII] observations, respectively.

We reduced the ALMA data with the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007) in the standard manner with the scripts provided by the ALMA Observatory. We produced the continuum images and line cubes by running the CLEAN algorithm with the tclean task. For continuum, we flagged the calibrated visibility in the expected frequency ranges of the lines. We executed the tclean routines down to the 1σ level with a maximum iteration number of 10000 in the automask mode with the subparameters determined by the recommendations of the ALMA automasking guide.¹ For cubes, we applied continuum subtraction to the calibrated visibility with the uvcontsub task by using the line-free frequency. We fit the continuum along channels at least 500 km s⁻¹ away from the expected line centre. We tried the subtraction with fitorders 0, 1, and 2. For [OIII], the automasking and cleaning worked best for fitorder 0, and for [NII] the results were similar for all fitorders. We therefore chose to use fitorder 0 for both [OIII] and [NII] continuum subtraction. We adopted a spectral channel width of 20 km s⁻¹ and performed the CLEAN algorithm in each channel in the same manner as the continuum map. In both cases, we used natural weighting to maximize the sensitivity and applied the multiscale deconvolver with scales of 0 (i.e. point-source), 1, and 3 times the beam size. We list the synthesized beam size and the standard deviation of the pixel values in the final natural-weighted maps and cubes in Table 1.

3 RESULTS

3.1 Detection

In Fig. 1, we show the velocity-integrated moment 0 maps² and spectra for the [NII] and [OIII] lines (along with the [CII] and

<table>
<thead>
<tr>
<th>ALMA band</th>
<th>Target line/continuum</th>
<th>Beam size (arcsec²)</th>
<th>Sensitivity (mJy beam⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>[CII]</td>
<td>0.24 ± 0.22</td>
<td>0.02</td>
</tr>
<tr>
<td>7</td>
<td>[NII]</td>
<td>1.19 ± 0.98</td>
<td>0.02</td>
</tr>
<tr>
<td>8</td>
<td>[OIII]</td>
<td>0.33 ± 0.28</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>[O52]</td>
<td>0.51 ± 0.42</td>
<td>0.42</td>
</tr>
</tbody>
</table>

¹https://casaguides.nrao.edu/index.php/Automasking_Guide
²Produced using the SPECTRAL-CUBE package in PYTHON (Ginsburg et al. 2019).
Figure 1. Velocity-integrated moment-0 map (left) and spectrum (right) for all four lines. We show two apertures for each line: the aperture used to extract the spectrum shown as an empty black ellipse, and the aperture used to extract the flux shown as an empty dotted ellipse. The former is customized to each line to extract the best possible spectrum. The latter, common aperture (see Section 3.2), has the same size and location for all lines to ensure that we use the same physical region to calculate line ratios and estimate metallicity. The beam size is shown by a filled grey ellipse. The highlighted spectral line bins are based on the [C158] line width of −180 to +200 km s$^{-1}$. No smoothing is applied.
[O88] detections from previous studies). The [N122] and [O52] lines show significance levels of 5.0σ and 3.7σ at the peak pixel, respectively. The respective significance is 3.4σ and 3.8σ in the aperture optimized to each line (Fig. 1), and 3σ and 1.4σ in the common aperture (see Section 3.2). The morphology of the [O52] line is spatially extended (well beyond the beam size), consistent with the spatial position and rough extent of the rest-frame UV continuum observed with the Hubble Space Telescope (HST; Watson et al. 2015). Given the consistency with HST, we conclude that we achieve the first detection of the faint FIR lines of [O52] and [N122] at z > 7.

### 3.2 Flux measurement

To perform a fair photometric comparison by analysing the same regions of the galaxy, we use a common aperture to extract the enclosed flux for the four lines and the underlying continua for [N122] and [O88]. The common aperture was selected to get the best estimate of the weakest lines, [O52] and [N122]. We use this common aperture for all our calculations. To find the best common aperture, we plotted the signal-to-noise ratio (SNR) as a function of increasing aperture radius for both [O52] and [N122]. For [O52], the highest SNR was at 0.5 arcsec radius beyond which noise began to dominate. For [N122], the optimal aperture radius was around 1.0 arcsec. As the beam size of the [N122] line was 1.19 × 0.98 arcsec², we chose not to use the optimal [O52] aperture to avoid flux loss in an aperture with diameter smaller than the largest beam size. Hence, we used a circular aperture with 1.1 arcsec radius to include most of the [N122] and [O52] flux. We also adopt a common velocity integration range of [−180 to +200] km s⁻¹ to estimate the line flux. This range is based on the ~2σ velocity width for the [C158] line as can be seen from the last panel of Fig. 1.

We use a circular aperture of 1.1 arcsec radius, centred at RA = 13:11:29.924 and Dec. = −01:19:18.710 (J2000). The aperture was chosen to include both the [O52] and [N122] lines, which is slightly larger than the detectable [O52] emission region (see Figs 1 and 2). This aperture also encompasses the central [C158] and [O88] emission regions. We ensured that the aperture size is not smaller than the beam size of our worst resolution image ([N122]). The fluxes and corresponding luminosities are shown in Table 2.

To test whether the difference in resolution affects our flux measurement, we tapered the higher resolution [O88] map to match the lower resolution [O52] and [N122] maps. The fluxes measured were consistent with the values reported in Table 2 within ~1σ uncertainty. Additionally, we tested several elliptical and circular apertures that also encompassed all four line emissions, and the results were consistent.

The detection significance of the [O52] and [N122] lines is ~3.5σ. To test the significance of the line detection further, we employed a moving spectral window and produced several moment-0 maps with mid-points across the velocity axis. Then we performed a systematic search for off-centre sources in each moment-0 map using a 1.1 arcsec circular aperture. While for [N122], we found no other sources with ≥3.5σ significance, we did find a few of them for [O52]. However, these did not have extended spatial morphologies like the central source. Moreover, [O52] was only used to derive an upper limit (see Section 3.3.1), so if the detection significance is lower, our upper limit still holds.

### 3.3 Metallicity constraint

In this section, we obtain a constraint for the metallicity, Z, of A1689-zD1 in a series of steps. We first derive the electron density, nₑ, using the [O III] line ratio. We then combine this with the 88 to 122 µm dust continuum ratio to derive the ionization parameter, U. Finally, using U and the [O VIII] to [N II] line luminosity ratio, we constrain Z. The flux ratios could in principle be affected by differential magnification, which in turn depends on the lensing model assumed. However, in this case, since we are calculating integrated galaxy properties in a common aperture and all the lines and continua...
are mostly cospatial, differential magnification is likely to be small, only of the order of a few per cent.

### 3.3.1 [O III] ratio

The ratio of the [O III] to [O II] luminosity is independent of both Z and U as both lines originate from the same ion, and of the temperature, because the energy difference between these two states is small compared to the typical gas temperature in the ionizing regions of the galaxy. It is therefore a robust probe of \( n_e \) up to \( 10^4 \) or even \( 10^5 \) \( \text{cm}^{-3} \) (Paly et al. 2012; Pereira-Santaella et al. 2017; Zhang et al. 2018; Yang & Lidz 2020).

Fig. 3 shows the theoretical relationship between the [O III] line ratio and \( n_e \). The [O III] to [O II] ratio for A1689-zD1 in the common aperture is plotted as a horizontal purple line with 1σ uncertainty plotted as the corresponding shaded purple region. We derive a nominal value of \( n_e \sim 55 \text{ cm}^{-3} \) for the electron density. Including the 1σ uncertainty on the ratio, we obtain 1σ and 2σ upper limit of \( n_e \leq 260 \) and 485 \( \text{cm}^{-3} \).

Our density determination assumes that the gas is optically thin and in thermodynamic equilibrium at a temperature of 10000 K. The upper limit is less than \( 10^3 \) \( \text{cm}^{-3} \) for any temperature between 5000 and 20000 K. In the following analysis, we adopt the 1σ bound of \( n_e \sim 260 \text{ cm}^{-3} \) to propagate into our uncertainty calculation.

### 3.3.2 Dust continuum ratio and U

The ratio of the continuum at 88 and 122 \( \mu \text{m} \) can be used to constrain \( U \), with some dependence on the density (Rigopoulou et al. 2018). We assume a 1σ density range with an upper bound of 260 \( \text{cm}^{-3} \) from the [O III] line ratio and a lower bound of about 10 \( \text{cm}^{-3} \) (corresponding approximately to a uniform distribution of \( 2 \times 10^{10} \text{M}_\odot \) in gas over the galaxy area). While this lower bound is somewhat arbitrary, it is the upper density bound that influences how low the metallicity can be. A lower density would result in higher metallicity and ionization parameter. In Fig. 4, we plot the continuum ratio as a function of \( U \) based on CLOUDY modelling over these density bounds from Pereira-Santaella et al. (2017). We show the ratio for A1689-zD1 with 1σ uncertainty regions. The extreme values of this uncertainty region are then propagated through the model at the extreme values of the density range derived in Section 3.3.3. From this, we infer a value of \(-1.7 \leq \log U \leq -0.8\) within the 1σ uncertainty range.

### 3.3.3 [O III]/[N II] ratio and the metallicity

Since the [O III] and [N II] lines have similar critical densities, their ratio is nearly independent of the density. However, it does depend on \( Z \) and \( U \). Fig. 5 plots the ratio as a function of \( Z \) for different model tracks of \( U \), once again using the Pereira-Santaella et al. (2017) model. While the model does hold beyond \( U > -2 \), this parameter space was only explored in their work for galaxies with an active galactic nucleus (AGN). Non-AGN galaxies generally do not have \( U > -2 \), but A1689-zD1 appears to be an exception with a high \( U \) despite not having any appreciable AGN activity. We therefore extrapolate the non-AGN Pereira-Santaella et al. (2017) model plot to higher values of \( U \) to accommodate the measurements for A1689-zD1. Since these extrapolated model values are in agreement with the numbers in the Harikane et al. (2020) models presented below, which is also CLOUDY based, and does extend all the way up to \( U = -0.5 \), we are confident that the extrapolation is valid.

As before, the ratio for A1689-zD1 is indicated with the 1σ uncertainty regions. Once again, we derive the uncertainty range
on metallicity by propagating the extreme values of the uncertainty region on the [O88]/[N122] ratio through the model curves at the extreme values of the log U measurements from Section 3.3.2. We thus find $0.9 \lesssim Z_{Z_{\odot}} \lesssim 1.3$. As mentioned in Section 3.3.2, if we were to allow lower densities, $U$ and in turn, $Z$, would be higher.

For comparison, we use models from Harikane et al. (2020) with metallicity-dependent N/O and C/O ratios. These are plotted in Fig. 6. The model assumes that the nitrogen-to-oxygen abundance ratio depends on the metallicity due to secondary nucleosynthesis (see Section 4.2). This in turn uses the relation presented in Kewley & Dopita (2002) in the same manner as Nagao et al. (2011). With this model, we find $Z_{Z_{\odot}} \sim 1$ to 2, and log $U \sim -0.5$ to $-2$ (with $n_{H} \sim 10$ to 100 cm$^{-3}$) roughly consistent with the estimates based on Rigopoulou et al. (2018).

Despite both models being CLOUDY based, the slight difference in metallicity estimate may arise from the different assumptions made in each one. For instance, Harikane et al. (2020) assumes a Chabrier initial mass function (IMF) and Pereira-Santaella et al. (2017) assumes a Kroupa IMF. In addition, we use a modified Harikane et al. (2020) model with metallicity-dependent nitrogen abundance, but a similar modification was not made for Rigopoulou et al. (2018) model. Regardless of these differences, metallicities significantly below the solar value do not reproduce our line ratios with either the Rigopoulou et al. (2018) or Harikane et al. (2020) model.

None the less, there is some uncertainty associated with the model curves presented here. First, there is some scatter in the N/O abundance to metallicity conversion (e.g. Liang et al. 2006). Additionally, CLOUDY model curves have a model uncertainty of the order 10–20 per cent as discussed in Pereira-Santaella et al. (2017), comparable to metallicity models based on optical emission lines. Although, as discussed in e.g. Croxall et al. (2013), models relying on FIR lines remove the heavy dependence on temperature that plagues optical emission lines.

3.4 [O88]/[C158] ratio and the PDR covering fraction

The ionization energies of [OIII] (35.1 eV) and [NII] (14.5 eV) are higher than that of H (13.6 eV), whereas the ionization energy of [C158] (11.2 eV) is lower than that of H. Hence, the [C158] emission comes from the cold atomic components, photodissociation regions (PDR), and HII regions, whereas the emission from the other three lines comes exclusively from the HII regions. Therefore, the ratio of [C158] to any of the other three lines can be used to estimate the PDR covering fraction, i.e. the extent of the ionized H gas compared to the neutral H gas (e.g. Cormier et al. 2019; Harikane et al. 2020).

In Fig. 7, we plot model curves for [C158] luminosity assuming PDR covering fractions of 0 and 1. The measurements for A1689-zD1 favor a model with PDR fraction close to 1, i.e. dominated by neutral atomic gas.

3.5 Dust-to-metals ratio

The total gas mass for A1689-zD1 is based on the sum of the atomic and molecular masses. We determine the atomic gas mass from the relation between the [C158] line luminosity, metallicity, and the atomic gas mass from Heintz et al. (2021). We find $M_{H} = 1.7^{+0.7}_{-0.5} \times 10^{10} M_{\odot}$. This includes the scatter in the relation and the statistical error added in quadrature.

Assuming most of the gas is in the atomic phase, the total gas mass is between 1.2 and $2.4 \times 10^{10} M_{\odot}$. Using a solar metal fraction of about 1/100 and a dust mass of $1.7^{+0.7}_{-0.3} \times 10^{7} M_{\odot}$ (Bakx et al. 2021), the corresponding dust-to-metals mass ratio (DTM) for A1689-zD1

Figure 5. [O88] to [N122] line ratio as a function of $U$ and $Z$ (adapted from Rigopoulou et al. 2018 and extrapolated above $-2.0$). Measurements for A1689-zD1 are shown in purple, just as in Fig. 4. Also as in Fig. 4, the uncertainty range on log $U$ is given by the intersection of the extreme ends of the horizontal shaded purple region with the model curves corresponding to the extreme values (dotted grey curve for lower limit and dashed grey curve for upper limit) of our log $U$ estimate from Section 3.3.2.

Figure 6. Model curves at various metallicities and densities for the [O88] luminosity/SFR ratio as a function of the [N122] luminosity/SFR ratio, based on Harikane et al. (2020). Increasing marker size represents an increase in log $U$, within the range $-4$ to $-0.5$. The measurements for A1689-zD1 are shown as a purple star with uncertainties.
4 DISCUSSION

Several striking features are derived from the line ratios reported here. First, the metallicity is close to solar, which deviates strongly from the expected mass–metallcity evolution towards high z.

Second, the nitrogen abundance is in excess of oxygen, indicating that the star formation in the galaxy must be old enough to have produced secondary nitrogen through intermediate-mass stellar envelopes, i.e. at least 250 Myr (Henry, Edmunds & Köppen 2000), pushing the formation age of the system back to $z > 10$.

Third, though this system is known as a prototypical dusty normal galaxy at this epoch, it seems to be deficient in dust compared to its total metal content.

4.1 Evolution of metal abundance

The most reliable metallicity estimates for star-forming galaxies come from back-lighting absorption studies, e.g. gamma-ray burst (GRB) afterglows. All show metallicities substantially below 0.1 solar (Salvaterra 2015) at $z \sim 6$. With some assumptions on density and temperature, Jones et al. (2020) have estimated metallicities for a handful of $z > 7$ galaxies using the relative strength of the [OIII] line to the total SFR and find metallicities ranging from 8 to 36 per cent of the solar value. Using a similar method to the one used here, but assuming log $U$, Novak et al. (2019) find solar or possibly supersolar metallicity for the ISM of the host galaxy of the quasar J1342+0928 at $z = 7.54$, demonstrating that such a high metallicity is not unique at $z > 7$. Over the next 13 Gyr, if such a high-metallicity galaxy is to increase its mass, it must do so mainly via dry mergers and not through a lot of star formation that would lead to supernova explosions that would substantially increase the metal content.

4.1.1 The fundamental metallicity relation

Galaxies up to $z \sim 2.5$ lie on a plane in 3D space spanning $M_*$, Z, and SFR. While there appears to be no evolution between local Sloan Digital Sky Survey (SDSS) galaxies at $z \sim 0$ and those at $z \sim 2.5$, there is some evolution above $z \sim 2.5$ (Mannucci et al. 2010). We do not know how early these relationships are set-up in galaxies, but galaxies at $z \sim 3$ appear to lie 0.6 dex below the metallicity prediction of the lower $z$ calibrated fundamental metallicity relation (FMR) from Mannucci et al. (2010). Other studies have also found an evolution of the FMR relation with redshift (e.g. Stott et al. 2013; Torrey et al. 2018; Sanders et al. 2021).

Given the stellar mass and SFR for A1689-zD1, its metallicity is substantially higher than the $z \sim 3$ FMR by $\sim 1.25$ dex, and even the $z \sim 0$ FMR by $\sim 0.6$ dex. Hence, the measured metallicity of A1689-zD1 is inconsistent with the trend suggested by Mannucci et al. (2010) by about an order of magnitude in metallicity. A revised $z \sim 0$ FMR parametrization was presented by Curti et al. (2020), but A1689-zD1 deviates from this relation well by about 1 dex.

The reason for the deviation may be an inaccurate estimate of the stellar mass. The current value of $2 \times 10^9 M_\odot$ is determined from rest-frame optical spectral energy distribution (SED) fitting, which could be heavily dust obscured. The SFR of A1689-zD1 is more than 90 per cent obscured. While the obscuration of the stellar mass is unlikely to be as high as this, it could still be substantial. With a stellar mass of $10^{10} M_\odot$, i.e. a factor of 80 per cent obscuration of the stellar mass, the deviation from the $z \sim 0$ FMR decreases to only 0.1 dex (although the deviation from the $z \sim 3$ FMR is still 0.7 dex). A stellar mass at least as large as the gas mass is required to produce all the metals in a solar metallicity system assuming a Chabrier or Kroupa IMF. Therefore such a high stellar mass is reasonable. However, it is hard to imagine dust obscuration much greater than this.

Another potential reason for the discrepancy might be the assumed N/O ratio in our models based on Rigopoulou et al. (2018) and Harikane et al. (2020). Both models assume the relation between the N/O ratio and metallicity calibrated in the local Universe. However, we do not know the N/O–metallicity relation at $z \sim 7$. Some studies (e.g. Queyrel et al. 2009; Yabe et al. 2015) report a possible increase of the N/O ratio at fixed metallicity at redshift $z \sim 1.5$, while others do not at $z \sim 2$ (Kojima et al. 2017). If the N/O ratio does evolve, the estimated metallicity would decrease, and become more consistent with the FMR.

4.2 Nitrogen excess and the age of A1689-zD1

The metallicity estimate derived from the [OIII]/[NII]22 ratio depends on the overabundance of N with respect to O (Pereira-Santaella et al. 2017; Rigopoulou et al. 2018), a consequence of secondary nitrogen production that only becomes dominant at $Z_{\odot} > 0.25$ (e.g. Pilyugin, Grebel & Kniazev 2014; Vincenzo et al. 2016).

Henry et al. (2000) argue that the secondary production of nitrogen principally occurs in the asymptotic giant branch (AGB) phase of intermediate-mass stars (4–8 $M_\odot$), while O and C production continues to be dominated by high-mass stars or Type II supernovae. This leads to an increase in the N/O ratio with increasing abundance above $Z_{\odot} > 0.25$. However, it also introduces a delay of about 250 Myr, the main-sequence lifetime of these intermediate-mass stars, before the N/O ratio increase can occur.

The fact that we observe a relatively low [OIII]/[NII]22 ratio, and from it infer a metallicity significantly above 0.25 solar, suggests that the stellar age of this galaxy is at least several hundred million years. The galaxy must have therefore started forming stars at $z >$
Another way to resolve the tension would be to reduce the inferred metallicity. Reducing the metallicity by a factor of several, coupled with lowering the dust emissivity, could be enough to replicate the MW DTM. However, this would require either that the [NII22] line luminosity is over an order of magnitude lower than our estimate or that the N/O line ratio-to-metallicity conversion (Rigopoulou et al. 2018; Harikane et al. 2020) is very different at this redshift (see Section 4.1.1).

4.4 [C158] deficit and the initial mass function

We find no [C158] deficit (e.g. Hodge & da Cunha 2020) in A1689-zD1, similar to other some massive galaxies at z ~ 7 (e.g. Capak et al. 2015; Schaerer et al. 2020; Schouws et al. 2022a). Katz et al. (2022) claim that the deficit comes from low C/O abundance at high redshift, which in turn arises from enrichment by low-metallicity core-collapse supernovae with a top-heavy IMF with no AGB stars to provide carbon. Since most AGB stars take ~1 billion years to contribute substantially to the ISM, the presence of [C158]-bright sources at z ~ 7 mitigates against the hypothesis of a top-heavy IMF with carbon-deficient supernovae.

4.5 Metallicity variation across the galaxy

As the SNR and spatial resolution of the [NII22] data is much lower than that of the other lines, we could not create a resolved metallicity map. However, considering the fact that the [C158] and dust emission are stronger to the north-west side while the HST emission is stronger to the south-east (Knudsen et al., in preparation), the metallicity may vary across the galaxy. A distinct difference in the metallicity between the major components measured with higher SNR measurements could indicate that the system was in the process of merging (Knudsen et al. 2017; Wong et al. 2022).

5 CONCLUSIONS

We have measured [O52] and [NII22] for the first time in a reionization-epoch galaxy. These measurements, coupled with previous measurements of [O88] and [C158], and several dust continuum detections, have allowed us to determine the electron density and metallicity of the galaxy, subject to modelling uncertainties. A1689-zD1 appears to have approximately solar gas-phase metallicity, remarkably high and unusual for a normal galaxy at this epoch. The excess of nitrogen to oxygen indicates that the star formation in this galaxy started at least 250 Myr earlier, i.e. at z > 10. The galaxy also appears to be atomic gas dominated, and to have a low dust-to-gas ratio for its metallicity, possibly hinting at a low efficiency for dust production in galaxies at this epoch.

ACKNOWLEDGEMENTS

We thank the anonymous referee for insightful comments, and Shengqi Yang and Luca Di Mascoco for helpful discussions.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2013.1.01064.S; ADS/JAO.ALMA#2015.1.01406.S; ADS/JAO.ALMA#2016.1.00954.S; ADS/JAO.ALMA#2017.1.00775.S; and ADS/JAO.ALMA#2019.1.01778.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. The National Radio Astronomy
Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

DW and SF are supported in part by Independent Research Fund Denmark grant DFF-7014-00017. The Cosmic Dawn Center is funded by the Danish National Research Foundation under grant number 140. KK acknowledges support from the Knut and Alice Wallenberg Foundation. FR acknowledges support from the European Union’s Horizon 2020 Framework Programme under the Marie Sklodowska-Curie grant agreement no. 847523 ‘INTERACTIONS’.

DATA AVAILABILITY

The data used in the paper are available in the ALMA archive at https://almascience.nrao.edu. The derived data and models generated in this research will be shared on reasonable request to the corresponding author.

REFERENCES

Capak P. L. et al., 2015, Nature, 522, 455
Chartab N. et al., 2022, Nat. Astron., 6, 844
Fudamoto Y. et al., 2021, Nature, 597, 489
Ginsburg A. et al., 2019, radio-astro-tools/spectral-cube: v0.4.4 (v0.4.4).
Zenodo. Available at: https://doi.org/10.5281/zenodo.2573901
Hashimoto T. et al., 2019, PASJ, 71, 71
Kewley L. J., Nicholls D. C., Sutherland R. S., 2019, ARA&A, 57, 511
Maiolino R., Mannucci F., 2019, A&AR, 27, 3
Marrone D. P. et al., 2018, Nature, 553, 51
Schouws S. et al., 2022a, preprint (arXiv:2202.04080)
Yabe K. et al., 2015, PASJ, 67, 102

This paper has been typeset from a TeX/LaTeX file prepared by the author.