A solar metallicity galaxy at \( z > 7 \)? Detection of the [N \textsc{ii}] 122 \( \mu \)m and [O \textsc{iii}] 52 \( \mu \)m lines

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ABSTRACT

We present the first detection of the [N \textsc{ii}] 122 \( \mu \)m and [O \textsc{iii}] 52 \( \mu \)m lines for a reionisation-epoch galaxy. Based on these lines and previous [C \textsc{ii}] 158 \( \mu \)m and [O \textsc{iii}] 88 \( \mu \)m measurements, we estimate an electron density of \( \leq 500 \text{ cm}^{-3} \) and a gas-phase metallicity \( Z/Z_{\odot} \approx 1.1 \pm 0.2 \) for A1689-zD1, a gravitationally-lensed, dusty galaxy at \( z = 7.133 \). Other measurements or indicators of metallicity so far in galaxy ISMs at \( z \gtrsim 6 \) 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 \( z \sim 7 \) 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: galaxies: high-redshift – galaxies: individual: A1689-zD1 – galaxies: ISM – ISM: abundances – submillimetre: galaxies

1 INTRODUCTION

The frontier of the study of galaxy evolution has now moved to the epoch of reionisation, \( z \gtrsim 7 \), 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 et al. 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. 2022). 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 \textsc{ii}] 158 \( \mu \)m and [O \textsc{iii}] 88 \( \mu \)m (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; Hashimoto et al. 2019; Carniani et al. 2020; Sommovigo et al. 2021; Schouw et al. 2022a). Fewer than 10 galaxies have been detected in both [O88] and [C158] at \( z > 6 \) (Carniani et al. 2017; Hashimoto et al. 2019; Tamura et al. 2019; Bakk et al. 2020; Harikane et al. 2020), and only three 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 ionisation 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 \textsc{iii}] 52 \( \mu \)m and [N \textsc{ii}] 122 \( \mu \)m (hereafter [O52] and [N122] respectively) in addition to [O88] and [C158].
However, this poses an observational challenge because while [O88] and [C158] are bright, [N122] is relatively faint and difficult to detect at $z > 6$. There have been [N122] 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 [O52] 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 [O52] at $z > 6$.

In this work, we report on the first measurement of the [O52] and [N122] lines for a non-quasar galaxy at $z > 6$. Together with previous [O88] and [C158] measurements (Akins et al. 2022; Wong et al. 2022; Knudsen et al. in prep.), we now have four FIR line detections for the gravitationally-lensed reionisation-epoch, dusty, normal galaxy A1689-zD1 at $z = 7.133$, making it the ideal candidate to study ISM conditions in re-ionisation 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 VLT/X-shooter data, and it was shown to be a dusty galaxy with 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. Fudamoto et al. 2021; Ferrara et al. 2022; Schouws et al. 2022b; Laporte et al. 2017). A1689-zD1 has now been detected in strong [C158] and [O88] 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 prep.). The galaxy has also been detected in four continuum bands allowing an accurate measurement of its dust temperature and mass (Baxk et al. 2021). The rich multi-wavelength data set makes it one of the best-studied re-ionisation-epoch galaxies.

In this paper, we report the measured line fluxes, and calculate ratios among the four lines and their underlying continua to characterise 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 prep.).

We adopt a Flat $\Lambda$CDM cosmology with $H_0 = 67.74$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3075$, and $\Omega_\Lambda = 0.6925$ (Planck Collaboration et al. 2016).

### 2 OBSERVATIONS AND METHODS

For the analysis presented in this work, we use the following the values for the stellar mass ($M_*$), dust mass ($M_d$), and star-formation rate (SFR) for the galaxy: $M_* = 1.7^{+0.7}_{-0.5} \times 10^{10}$ M$_\odot$ (Watson et al. 2015); total SFR = $37^{\pm 1} M_\odot$ yr$^{-1}$ (Akins et al. 2022); $M_d = 1.7^{+1.3}_{-0.7} \times 10^9$ M$_\odot$ (Baxk et al. 2021).

#### 2.1 [N122] and [O52] observations

Observations were carried out at the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile from November to December 2019 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 antennae with projected baselines of 15–313 m. Based on a source redshift of $z = 7.1332 \pm 0.0005$, securely determined with [C158] and [O88] (Wong et al. 2022, Knudsen et al. in prep.), 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 [N122] and [O52] lines fall in one or two spectral windows.

| ALMA Band | Target line/continuum | Beam-size [$''$] | Sensitivity [mJy beam$^{-1}$] |
|-----------|-----------------------|-----------------|------------------|
| 6         | [C158]                | $0.24 \times 0.22$ | 0.02 |
| 7         | [N122]                | $1.19 \times 0.98$ | 0.02 |
| 8         | [O88]                 | $0.33 \times 0.28$ | 0.12 |
| 9         | [O52]                 | $0.51 \times 0.42$ | 0.42 |
| 7         | continuum             | $1.18 \times 0.97$ | 0.06 |
| 8         | continuum             | $0.46 \times 0.40$ | 0.05 |

J1229+0203 and J1337–1257 were observed as the flux and bandpass calibrators. Phase calibration was performed by using observations of J1256–0547. The total on-source times were 200 minutes and 95 minutes for the [O52] and [N122] observations respectively.

We reduced the ALMA data with the Common Astronomy Software Applications package (CASA; 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 sub-parameters determined by the recommendations of the ALMA automasking guide. For cubes, we applied continuum subtraction to the calibrated visibility with the ucontsub task by using the line-free frequency. We fit the continuum along channels at least ±500 km/s away from the expected line centre. We tried the subtraction with fitorders 0, 1, and 2. For [O52], the automasking and cleaning worked best for fitorder 0, and for [N122] the results were similar for all fitorders. We therefore chose to use fitorder 0 for both [O52] and [N122] 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 maximise the sensitivity and applied the multi-scale deconvolver with scales of 0 (i.e. point source), 1, and 3 times the beam size. We list the synthesised 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 Figure 1, we show the velocity-integrated moment 0 maps and spectra for the [N122] and [O52] lines (along with the [C158] and [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 optimised to each line (Fig. 1), 3σ and 1.4σ in the common aperture (see Sec. 3.2). The morphology of the [O52] line is spatially extended (well beyond the beamsize), consistent with the spatial position and rough extent of the rest-frame UV continuum observed with the

1. https://casaguides.nrao.edu/index.php/Automasking_Guide
2. produced using the spectral-cube package in Python (Ginsburg et al. 2019)
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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 customised to each line to extract the best possible spectrum. The latter, common aperture (see Sec. 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.
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 [N\textsubscript{22}] and [O\textsubscript{88}]. The common aperture was selected to optimize the weakest lines, [O\textsubscript{52}] and [N\textsubscript{122}]. To find the optimal aperture, we plotted the signal-to-noise ratio (SNR) as a function of increasing aperture radius for both [O\textsubscript{52}] and [N\textsubscript{122}]. For [O\textsubscript{52}], the highest SNR was at 0.′′5 radius beyond which noise began to dominate. For [N\textsubscript{122}], the optimal aperture radius was around 1.′′0. As the beamsize of the [N\textsubscript{122}] line was 1.′′19 \times 0.′′98, we chose not to use the optimal [O\textsubscript{52}] aperture to avoid flux loss in an aperture with diameter smaller than the largest beamsize. Hence, we used a circular aperture with 1.′′1 radius to include most of the [N\textsubscript{122}] and [O\textsubscript{52}] flux. We also adopt a common velocity integration range of [-180 : +200] \text{ km s}^{-1} to estimate the line flux. This range is based on the ~ 2\sigma velocity width for the [C\textsubscript{158}] line as can be seen from the last panel of Fig. 1.

We use a circular aperture of 1.′′1 radius, centred at RA = 13:11:29.924 and Dec = −01:19:18.710 (J2000). The aperture was chosen to include both the [O\textsubscript{52}] and [N\textsubscript{122}] lines, which is slightly larger than the detectable [O\textsubscript{52}] emission region (see Figs. 1 and 2). This aperture also encompasses the central [C\textsubscript{158}] and [O\textsubscript{88}] emission regions. We ensured that the aperture size is not smaller than the beam-size of our worst resolution image ([N\textsubscript{122}]). 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 [O\textsubscript{88}] map to match the lower resolution [O\textsubscript{52}] and [N\textsubscript{122}] maps. The fluxes measured were consistent to the values reported in Table 2 within ~ 1\sigma 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 [O\textsubscript{52}] and [N\textsubscript{122}] lines is ~ 3.5\sigma. To test the significance of the line detection further, we employed a moving spectral window and produced several moment-0 maps with midpoints across the velocity axis. Then we performed a systematic search for off-centre sources in each moment-0 map using a 1.′′1 circular aperture. While for [N\textsubscript{122}], we found no other sources with \geq 3.5\sigma significance, we did find a few of them for [O\textsubscript{52}]. However, these did not have extended spatial morphologies like the central source. Moreover, [O\textsubscript{52}] was only used to derive an upper limit (see Sec. 3.3.1), so if the detection significance is lower, our upper limit still holds.

Table 2. Galaxy-integrated line and continuum measurements for A1689-zD1 using an aperture as described in Sec. 3.2. The luminosity has been corrected for lensing, but the flux is uncorrected.

| Line   | \( \lambda \) | Flux (Jy beam\(^{-1}\)) | Luminosity (L\(_{\odot}\)) |
|--------|---------------|---------------------------|---------------------------|
| [O\textsubscript{i}] | 52 \text{\mum} | 2.3 \pm 1.6 (Jy km s\(^{-1}\)) | 9.6 \pm 6.7 \times 10\(^{8}\) |
| [O\textsubscript{iii}] | 88 \text{\mum} | 5.75 \pm 0.38 (Jy km s\(^{-1}\)) | 1.40 \pm 0.09 \times 10\(^{9}\) |
| [N\textsubscript{ii}] | 122 \text{\mum} | 0.09 \pm 0.03 (Jy km s\(^{-1}\)) | 1.65 \pm 0.51 \times 10\(^{7}\) |
| [C\textsubscript{ii}] | 158 \text{\mum} | 3.60 \pm 0.07 (Jy km s\(^{-1}\)) | 4.84 \pm 0.10 \times 10\(^{8}\) |

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 [O\textsubscript{52}] as well as [N\textsubscript{122}] at \( z > 7 \).

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, \( n_e \), using the [O\textsubscript{i}] line ratio. We then combine this with the 88 to 122 \text{\mum} dust continuum ratio to derive the ionisation parameter, \( U \). Finally, using \( U \) and the [O\textsubscript{iii}] to [N\textsubscript{22}] 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 co-spatial, differential magnification is likely to be small, only of the order of a few per cent.

3.3.1 [O\textsubscript{i}] ratio

The ratio of the [O\textsubscript{52}] to [O\textsubscript{88}] luminosity is independent of both \( Z \) and \( U \) as both lines originate from the same ion, and of the tem-
perature, because the energy difference between these two states is small compared to the typical gas temperature in the ionising regions of the galaxy. It is therefore a robust probe of \( n_e \), up to \( 10^5 \) or even \( 10^5 \text{cm}^{-3} \) (Palay et al. 2012; Pereira-Santaella et al. 2017; Zhang et al. 2018; Yang & Lidz 2020).

Fig. 3 shows the theoretical relationship between the [O\textsc{iii}] line ratio and \( n_e \). The [O\textsc{ii}]/[O\textsc{iii}] ratio for A1689-zD1 in the common aperture is plotted as a horizontal purple line with 1\( \sigma \) 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 1\( \sigma \) uncertainty on the ratio, we obtain 1 and 2\( \sigma \) upper limit of \( n_e \leq 260 \) and 485 cm\(^{-3} \).

Our density derivation assumes that the gas is optically thin and in thermodynamic equilibrium at a temperature of 100 000 K. The upper limit is less than 10\(^5 \) cm\(^{-3} \) for any temperature between 5000 and 20 000 K. In the following analysis, we adopt the 1\( \sigma \) 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 \( \mu \)m and 122 \( \mu \)m can be used to constrain \( U \), with some dependence on the density (Rigopoulou et al. 2018). We assume a 1\( \sigma \) density range with an upper bound of 260 cm\(^{-3} \) from the [O\textsc{iii}] line ratio and a lower bound of about 10 cm\(^{-3} \) (corresponding approximately to a uniform distribution of \( 2 \times 10^{10} M_{\odot} \) 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 ionisation parameter. In Fig. 4, we plot the continuum ratio as a function of \( \log U \) based on CLOUDY modelling over these density bounds from Pereira-Santaella et al. (2017). We show the ratio for A1689-zD1 with 1\( \sigma \) 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 Sec. 3.3.3. From this, we infer a value of \(-1.7 \leq \log U \leq -0.8 \) within the 1\( \sigma \) uncertainty range.

### 3.3.3 [O\textsc{iii}]/[N\textsc{ii}] ratio and the metallicity

Since the [O\textsc{iii}] and [N\textsc{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 \( \log U \), once again using the Pereira-Santaella et al. (2017) model. While the model does hold beyond \( \log U > -2 \), this parameter space was only explored in their work for galaxies with an active galactic nucleus (AGN). Non-AGN galaxies generally do not have \( \log U > -2 \), but A1689-zD1 appears to be an exception with a high \( \log U \) 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 \( \log U = -0.5 \), we are confident that the extrapolation is valid.

As before, the ratio for A1689-zD1 is indicated with the 1\( \sigma \) uncertainty regions. Once again, we derive the uncertainty range on metallicity by propagating the extreme values of the uncertainty region on the [O\textsc{iii}]/[N\textsc{ii}] ratio through the model curves at the extreme values of the \( \log U \) measurements from Sec. 3.3.2. We thus find \( 0.9 \leq Z/Z_{\odot} \leq 1.3 \). As mentioned in Sec 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...
The ionisation energies of [O\textsc{iii}] (35.1 eV) and [N\textsc{ii}] (14.5 eV) are higher than that of H (13.6 eV), whereas the ionisation energy of [C\textsc{i}] (11.2 eV) is lower than that of H. Hence, the [C\textsc{i}] emission comes from the cold atomic components, photo-dissociation regions (PDR), and H\textsc{ii} regions, whereas the emission from the other three lines comes exclusively from the H\textsc{ii} regions. Therefore, the ratio of [C\textsc{i}] to any of the other three lines can be used to estimate the PDR covering fraction, i.e. the extent of the ionised 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 [C\textsc{i}] luminosity assuming PDR covering fractions of 0 and 1. The measurements for A1689-zD1 favour 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 [C\textsc{i}] line luminosity, metallicity and the atomic gas mass from Heintz et al. (2021). We find $M_{\text{H}_1} = 1.7^{+0.7}_{-0.5} \times 10^{10} M_\odot$. 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 $1.7^{+0.7}_{-0.5} \times 10^{7} M_\odot$ (Bakx et al. 2021), the corresponding dust-to-metals mass ratio (DTM) for A1689-zD1 is around 0.1. If there is significantly more gas in the system, say in the molecular phase, this will make the DTM even lower.

### 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-metallicity 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 et al. 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 8–36 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 super-solar 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 which 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 $M_\ast$, $Z$, 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-zD, 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 parameterisation was presented by Curti et al. (2020), but A1689-zD1 deviates from this relation as well by about 1 dex.

The reason for the deviation may be an inaccurate estimate of the stellar mass. The current value of $2 \times 10^8 \, M_\odot$ is determined from rest-frame optical 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 fundamental metallicity relation.

#### 4.2 Nitrogen excess and the age of A1689-zD1

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

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 $Z/Z_\odot \geq 0.25$. 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] 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 $z \sim 10$. This is somewhat at odds with the stellar age inferred from the SED analysis ($\sim 80$ Myr). However, as argued above, much of the stellar mass may be completely obscured.

The stellar mass inferred from the SED fitting is only detected as far as 4.6 $\mu$m, corresponding roughly to the V-band in the rest-frame. As indicated by the 80–90 per cent obscured SFR fraction, we can infer that the average extinction to most sightlines in the galaxy is high. As also indicated by the relatively modest extinction in the
UV-bright parts of the galaxy, the dust distribution is likely very patchy, with some low obscuration regions, and most of the galaxy completely extinguished (for example, a dust mass of $2 \times 10^7 \, M_\odot$ spread over about 1 kpc$^2$ gives an $A_V \sim 200$ [Watson 2011]). This suggests that the stellar mass of $2 \times 10^8 \, M_\odot$ inferred from the SED is only a lower bound, and the real stellar mass could be up to an order of magnitude higher. A stellar mass of $10^{10} \, M_\odot$ would lead to a characteristic age of about 300 Myr, consistent with the age required for the N/O overabundance.

We therefore suggest two things from these considerations: that A1689-zD1 may have a much higher stellar mass than previously inferred, and that its stellar age is $\geq 300$ Myr. Hence, it must have started forming stars at a significant rate at $z > 10$. This is consistent with the claims for significant $z > 10$ star-formation inferred from candidate $z \sim 9$ galaxies (e.g. Laporte et al. 2021).

4.3 Low dust formation efficiency at $z > 7$

With a metallicity estimate in hand, we can address the question of the dust-formation efficiency of a galaxy at $z \geq 7$ for the first time. We calculated in Sec. 3.5 a dust-to-metals mass ratio of about 0.1. This is significantly lower than the MW value. For a MW gas-to-dust ratio of 150 [Galliano et al. 2018], suitable for galaxies close to solar metallicity, the corresponding dust mass in A1689-zD1 for its inferred gas mass should be $1-2 \times 10^8 \, M_\odot$, an order of magnitude higher than the measured value of $1.7^{+1.3}_{-0.7} \times 10^7 \, M_\odot$.

Although there have been suggestions that the formation of dust may be less efficient at low metallicity (De Cia et al. 2016; Galliano et al. 2018), at solar metallicity, dust-formation efficiency is observed to be high. In other words, the DTM is expected to be close to the MW value of 0.5 at metallicities at least down to about 0.3 dex below solar, as is observed in low redshift galaxies [De Vis et al. 2019]. The small number of estimates from emission-line galaxies at $z \sim 2$ [Shapley et al. 2020] suggest that the DTM is constant at about 0.5 to that redshift at high metallicity too, with the caveat that for those galaxies the molecular mass was assumed to represent all the gas. Estimates of the DTM for systems detected in absorption indicate both a dependence on metallicity [De Cia et al. 2016] and no metallicity dependence [Zafar & Watson 2013; Wiseman et al. 2017].

Regardless, A1689-zD1 is therefore a unique case, indicating a low dust formation efficiency in spite of the high metallicity. The low dust formation efficiency could point to a gas mass much lower than we have inferred, indicating a breakdown of the [C158]-H$\alpha$ relation of Heintz et al. (2021), or a dust formation timescale longer than the stellar mass build-up or nitrogen-enrichment timescale of $\sim 250$ million years, or possibly a lack of high-emissivity dust originating in e.g. AGB stars. One caveat here is indeed the uncertainty in the emissivity of the dust. Local studies of the dust emissivity or dust mass absorption coefficient suggest lower emissivity by up to a factor of two in high density or higher temperature environments [Bianchi et al. 2022; Clark et al. 2019]. This factor would alleviate some of the tension we observe here, though not eliminate it entirely.

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 [N122] 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 Sec. 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 some other massive galaxies at $z \sim 7$ (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 $\geq 1$ billion years to contribute substantially to the ISM, the presence of [C158]-bright sources at $z \sim 7$ militates 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 [N122] 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 northwest side while the HST emission is stronger to the southeast (Knudsen et. al.(in prep.)), 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 [N122] for the first time in a reionisation-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.

A1689-zD1 has 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.

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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.

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