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Accurate dust temperature determination in a $z = 7.13$ galaxy

Tom J. L. C. Bakx,1,2,⋆ Laura Sommovigo,3 Stefano Carniani,4 Andrea Ferrara,3 Hollis B. Akins,4 Seiji Fujimoto,5,6 Masato Hagimoto,1 Kirsten K. Knudsen,6,7 Andrea Pallottini,4 Yoichi Tamura1 and Darach Watson5,6

1Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Aichi 4648602, Japan
2National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo 1818588, Japan
3Scuola Normale Superiore, Piazza dei Cavalieri 7, Pisa I-56126, Italy
4Department of Physics, Grinnell College, 1116 Eighth Ave., Grinnell, IA 50112, USA
5Cosmic Dawn Center (DAWN), Copenhagen, Denmark
6Niels Bohr Institute, University of Copenhagen, Jagtvej 128, Copenhagen, Denmark
7Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, Onsala SE 43992, Sweden

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ABSTRACT
We report ALMA Band 9 continuum observations of the normal, dusty star-forming galaxy A1689-zD1 at $z = 7.13$, resulting in a $\sim 4.6 \sigma$ detection at 702 GHz. For the first time, these observations probe the far-infrared spectrum shortward of the emission peak of a galaxy in the Epoch of Reionization (EoR). Together with ancillary data from earlier works, we derive the dust temperature, $T_d$, and mass, $M_d$, of A1689-zD1 using both traditional modified blackbody spectral energy density fitting, and a new method that relies only on the [C II] 158 $\mu$m line and underlying continuum data. The two methods give $T_d = (42^{+13}_{-7}, 40^{+13}_{-7})$ K, and $M_d = (1.7^{+1.3}_{-0.7}, 2.0^{+1.8}_{-1.0}) \times 10^7 M_{\odot}$. Band 9 observations improve the accuracy of the dust temperature (mass) estimate by $\sim 50$ per cent (6 times). The derived temperatures confirm the reported increasing $T_d$-redshift trend between $z = 0$ and 8; the dust mass is consistent with a supernova origin. Although A1689-zD1 is a normal UV-selected galaxy, our results, implying that $\sim 85$ per cent of its star-formation rate is obscured, underline the non-negligible effects of dust in EoR galaxies.

Key words: dust, extinction – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: individual: (A1689-zD1) – submillimetre: galaxies.

1 INTRODUCTION

Atacama Large Millimetre/submillimetre Array (ALMA) observations have revealed the presence of dust in galaxies approaching the epoch of reionization (EoR; e.g. Capak et al. 2015; Willott et al. 2015; Barisic et al. 2017; Laporte et al. 2017). This was somewhat surprising, since UV studies mapping out the cosmic star-formation rate density (SFRD) to $z \sim 10$ suggested a dearth of dust at the high-redshift end based on the blue UV slopes of low-stellar mass high-$z$ galaxies ($\beta_{UV}$; e.g. Finkelstein et al. 2015; Bouwens et al. 2016). Initially, the strong far-infrared (FIR) emission at $z > 7$ revealed by ALMA observations was attributed to the presence of unexpectedly large dust masses ($M_d$) in the observed high-$z$ galaxies, which was hard to reconcile with known dust production mechanisms that operate on that time-scale (predominantly SN and grain growth; see Leśniewska & Michałowski 2019 and references therein for the latest constraints).

This resulted in the so-called dust budget crisis, which also impacted star-formation history (SFH) estimates of high-redshift galaxies (e.g. Mawatari et al. 2020; Roberts-Borsani, Ellis & Laporte 2020). The stringent constraints on SNe dust production, coupled with the large deduced dust masses at $z > 7$, required very early stellar populations originating at $z \sim 14$ (Tamura et al. 2019). However, the conclusions on the dust masses were heavily dependent on the assumed (cold) dust temperatures ($T_d \sim 30$–$40$ K) for these high-$z$ sources, since in most cases only a single data point was available in the FIR continuum. Recent observations (e.g. Bakx et al. 2020) and theoretical studies (e.g. Behrens et al. 2018; Sommovigo et al. 2020) have suggested the presence of warm dust in several high-$z$ galaxies ($T_d > 60$ K), alleviating the large dust mass requirements set by their observed $L_{FIR}$ ($M_d \propto T_d^{(4+\beta_d)}$ at fixed $L_{FIR}$, where typically $1.0 < \beta_d < 3.0$). Unfortunately, the large uncertainties on derived $T_d$ at high-$z$ still hinder accurate SFH studies.

Partially due to the lack of knowledge on the dust temperature at high-$z$, the total fraction of obscured star-formation beyond $z > 4$ is also largely unknown (Novak et al. 2017; Casey et al. 2018; Bouwens et al. 2020; Gruppioni et al. 2020; Schouws et al. 2021; Talia et al. 2021; Zavala et al. 2021). This has strong implications for the cosmic SFRD; for example, some of these recent works suggest that there is no steep drop-off in SFRD at $z > 3$ (e.g. Gruppioni et al. 2020), which could indicate that we might be underestimating the contribution of highly obscured systems to the SFRD at $z > 3$ due to the bias towards UV bright objects. On top of that, most studies calculate the obscured star-formation rates and FIR luminosities of single sources either by assuming a dust temperature, and/or by

* E-mail: bakx@phys.nagoya-u.ac.jp
between these regions in several sources at z. However, observations suggest the possibility of spatial separation that the UV and dust-emitting regions to be cospatial, relying on the UV relation would impact the results of galaxies at high-z. Notably, the estimated dust mass of the UV-emission seen in Knudsen et al. (2017), a deviation IRX-βUV relation would impact the results of galaxies at high-z (Fudamoto et al. 2020; Le Fèvre et al. 2020) and will impact re-emission studies (e.g. MAGPHYS; da Cunha, Charlot & Elbaz 2008 and CIGALE; Boquien et al. 2019) which will be prevalent in the ALMA + JWST era.

In this letter, we use the band 9 observations to estimate the dust properties of a z = 7.1 galaxy from the spectrum directly in order to measure the obscured star-formation directly. We describe the source and data in Section 2, the fitting techniques in Section 3, and the implications in Section 4.

### Table 1. Continuum and fitting properties of A1689-zD1.

| Band  | λ [mm] | F_{int} \left( \mu \text{Jy}\right)^{-1} | Reference |
|-------|--------|-----------------------------------------|-----------|
| 9     | 0.427  | 154 ± 37                                | This work |
| 8     | 0.728  | 180 ± 39                                | Inoue et al. (2020) |
| 7     | 0.873  | 143 ± 15                                | Knudsen et al. (2017) |
| 6     | 1.33   | 60 ± 11                                 | Watson et al. (2015) |

**Notes.** †Corrected for the magnification assuming μ = 9.3 from Knudsen et al. (2017). ‡β_d is fixed to 2.03.

scaling directly from the infrared excess (IRX = L_{IR}/L_{UV})-βUV relation. Both approaches suffer from the inherent uncertainty in dust temperature (since obscured SFR and IRX both scale with T^{4+β_d}).

Moreover, the validity of IRX-βUV relation at high-z demands that the UV and dust-emitting regions to be cospatial, relying on the absorbed UV emission to be re-emitted at FIR wavelengths. However, observations suggest the possibility of spatial separation between these regions in several sources at z = 4 - 6 (e.g. Faisst et al. 2017) and at z ∼ 7 - 8 sources (e.g. Carniani et al. 2017; Laporte et al. 2019, and Tamura et al., in preparation). In fact, this spatial separation scenario between UV and IR is also supported by theoretical studies and simulations (Behrens et al. 2018; Cochrane et al. 2019; Liang et al. 2019; Somm moggio et al. 2020). A deviating IRX-βUV relation would impact the results of galaxies at high-z (Fudamoto et al. 2020; Le Fèvre et al. 2020) and will impact re-emission studies (e.g. MAGPHYS; da Cunha, Charlot & Elbaz 2008 and CIGALE; Boquien et al. 2019) which will be prevalent in the ALMA + JWST era.

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### 2 TARGET AND OBSERVATIONS

A1689-zD1 was identified in Bradley et al. (2008) as a bright (m_{AB} ∼ 25) z > 7 galaxy. Due to the foreground galaxy cluster (A1689; Struble & Rood 1999), it is magnified by μ ∼ 9.3 (Knudsen et al. 2017). Its intrinsic UV magnitude indicates it is a sub-L* galaxy representing the bulk of galaxies at z = 7 (Ono et al. 2018). Band 6 observations at 1.3 mm by Watson et al. (2015) reported the first detection of dust beyond redshift 7, and indicated an intrinsic star-formation rate of ∼12 M_⊙ yr⁻¹. Notably, the estimated dust mass of this normal galaxy (assuming 35 K) was found in tension to SFH and dust production estimates in Lesniewska & Michałowski (2019).

†Throughout this paper, we assume a flat Λ-CDM cosmology with the best-fit parameters derived from the Planck results (Planck Collaboration XIII 2016), which are Ω_m = 0.307, Ω_Λ = 0.693 and h = 0.678.

‡While μ is high, there is only little shear, and we do not account for any differential lensing effects in this paper.

In this letter, we combine the existing data on A1689-zD1 reported in Watson et al. (2015), Knudsen et al. (2017), and Inoue et al. (2020) with archival band 9 data from (Program ID: 2019.1.01778.S, P.I. D. Watson), see Table 1. We use the [C II] luminosity as reported in Knudsen et al. (in preparation), which is (6.1 ± 0.7) × 10^8 L_⊙, and use their value for spectroscopic redshift, z = 7.13.

For the band 9 (Baryshev et al. 2015) data, the source was observed for 95 min. in baselines ranging from 14 to 312 m. The lower and upper sidebands covered the contiguous frequency ranges of 690.4-697.6 and of 706.5-713.6 GHz. We assume a typical flux accuracy of 10 per cent. The continuum image is produced with CASA pipeline version 5.6.1-8 (McMullin et al. 2007), using natural weighting, a taper of 0.5 arcseconds, and excluding any channels within 1000 km/s of the [O III] 52μm emission at 711.4 GHz. Fig. 1 shows the resulting image with a 0.61 by 0.67 arcsecond beam with a beam position angle of 75°, with an r.m.s. level of 210 μJy beam⁻¹. Using CASA’s IMFT routine, we spatially integrate the emission using a 2D Gaussian profile. This results in a flux of 1.43 ± 0.31 mJy (∼4.6σ; excluding calibration flux), with an apparent (or lensed) beam-deconvolved size of 0.81 ± 0.26 by 0.38 ± 0.22 arcsec at a position angle of 44 ± 38°. The emission appears cospatial to the UV-emission seen in Knudsen et al. (2017), although we leave further discussion of this to Knudsen et al. (in preparation).

### 3 METHODS

#### 3.1 Spectral fitting

Fig. 2 shows the modified black body (equation 8 in Sommogvio et al. 2021) fitted to the continuum points reported in Table 1. We use equations (12) and (18) from da Cunha et al. (2013) to account for the heating of dust by and decreasing contrast against the CMB, respectively. We approximate the dust mass absorption coefficient (κ_d) as κ_d ~ (μ/v)_{μJy}^β_d, with (κ_d, μ, v) as (10.41 cm²/g, 1900 GHz) from Draine (2003). We use the emcee MCMC-fitting routine, and allow M_d, T_d, and β_d to vary freely using flat priors, resulting in a...
Figure 2. We fit a modified black body (red line and fill) to the observed data points of A1689-zD1, including the band 9 data point (star). The [CII]-based spectrum (blue line and fill) is fit solely to the 158 μm continuum data point (blue), and it predicts a consistent galaxy spectrum, providing confidence in the [CII]-based method for this specific source even at 50 μm rest-frame. For comparison, the dashed red lines show the spread in SEDs fitted without band 9 data, which results in a twice larger error in dust temperature, and a sixfold increase in the error in dust mass.

3.2 Dust temperature from [CII] emission

We use the novel method proposed in Sommovigo et al. (2021) to derive the dust temperature in galaxies, based on the combination of 1900 GHz continuum and the overlying [CII] line emission. We provide a brief summary of this method below; for further details and verification of this method on 19 local galaxies, three galaxies at z > 4, and a z ~ 6.7 simulated galaxy, we refer to Sommovigo et al. (2021).

We relate the observed [CII] luminosity to the total dust mass via a dust mass and a gas-to-dust ratio (assumed to scale linearly with the metallicity, which is justified down to Z = 0.1 Z⊙, see James et al. 2002; Draine & Li 2007; Galliano, Dwek & Chianial 2008; Leroy et al. 2011). The gas mass and [CII] luminosity are related through a conversion factor Mgas = α[CII]L[CII]. This conversion factor α[CII] is analytically derived from the combination of the de Looze relation (De Looze et al. 2014) and the Kennicutt–Schmidt relation (Kennicutt 1998, hereafter KS). Two parameters are added in the expression for α[CII] in order to account for both (i) the expected offset from the KS-relation (i.e. the burstiness of the SF of a galaxy parametrized by κs) and (ii) the observed larger extension of [CII] with respect to stellar emission at high-z (up to 1.5–3 times larger; Carniani et al. 2017, 2018, 2020; Matthee et al. 2017, 2019; Fujimoto et al. 2019, 2020, 2021; Ginolfi et al. 2020; Herrera-Camus et al. 2021).

We fit a modified blackbody to derive the dust temperature using the neighbouring continuum emission at ~1900 GHz rest-frame wavelength, assuming a fixed βd = 2.03, which is based on the Draine (2003) predictions for the Milky Way and the Small Magellanic Cloud. Within this fitting routine, both the burstiness parameter (κs) and the metallicity are largely uncertain. In order to constrain the dust temperature, two broad physical constraints are placed: (i) The dust mass cannot exceed the maximal dust mass producible by supernovae (SNe), assuming all the SNe metal yield (~2 M⊙ per SN) ends up locked into dust grains; (ii) The dust-obscured star formation (Kennicutt 1998; Madau & Dickinson 2014), cannot significantly (by 1 order of magnitude) exceed the SFR deduced from [CII] using the relation from De Looze et al. (2014) for starbursts. Applying our method to A1689-zD1, we find a dust temperature Td = 40^+13^−10 K and mass of MD = 2.0 × 10^7 M⊙. These values are obtained assuming a wide range of values for the metallicity Z = 0.2–1 Z⊙, and the burstiness parameter κs = 1 – 50 (Vallini et al. 2021). For our further discussion of dust production mechanisms, we note that the removal of the dust production constraint does not influence the derived quantities.

4 IMPLICATIONS

The dust temperature and mass estimates from the [CII]-based method agree with the results from the direct SED fitting, which adds confidence to the method from Sommovigo et al. (2021). As shown in Table 1, band 9 observations reduce the uncertainty in the dust temperature by ~50 per cent, which translates to much-improved estimate on the FIR luminosity and dust mass estimate. In Fig. 2, we show the observed peak emission wavelength (λpeak,obs) of galaxies at z > 5 against our current best-estimates for Td and βd. To guide the eye, we include the trend of λpeak,obs with Td for βd = 1 – 2 at z = 7.1. We also overlay the wavelengths of the ALMA bands 7 through 10. We calculate this λpeak,obs using

$$\lambda_{\text{peak, obs}} = \frac{14.42 \times (1 + z) (T_d/K)^{-1}}{W(-a e^{-a}) + a} \, \mu m$$

where a = 3 + βd and W is the Lambert W function. This is the wavelength at which the continuum spectrum Fiver peaks in frequency units (e.g. Fig. 2). This is an important distinction to keep in mind when visualising λobs,peak from the analogy to Wien’s law, which provides the peak of the spectrum when reported in wavelength units Fλ.

Particularly for galaxies at lower redshifts and at higher temperatures, short-wavelength observations are crucial to estimate the dust temperature, whereas band 8 might be able to probe the emission peak for cold z > 8 galaxies. In the foreseeable future, the high bands of ALMA (9 and 10) are the only instrument capable of probing this regime, until such missions as the Origins Space Telescope (Meixner et al. 2019).

3This IR luminosity-to-SFR conversion factor, 1.73 × 10^{-10} M⊙ yr^{-1}/L⊙, is valid for a Salpeter 1–100 M⊙ IMF, which we assume consistently throughout the paper.

4https://asd.gsfc.nasa.gov/firs/docs/
Accurate estimates of the dust-obscured fraction of the star-formation rate require strong constraints on the dust temperature, as SFR\textsubscript{obs} ∝ L\textsubscript{FIR} ∝ M\textsubscript{d}β\textsubscript{d}/T\textsubscript{d}^4. Our band 9 observations confirm this relatively-cold (T\textsubscript{d} ≈ 40–60 K) system has a very large obscured fraction of the SFR around ∼85 per cent (SFR\textsubscript{obs} = 33 ± 9 M\textsubscript{☉} yr\textsuperscript{−1}), whereas\textsuperscript{5} SFR\textsubscript{UV} = 5.7 ± 0.3 M\textsubscript{☉} yr\textsuperscript{−1}, even though it was selected to be UV-bright. The dust-obscured ratio is higher than the 61 per cent found for the typically more-massive ALPINE survey selected to be UV-bright. The dust-obscured ratio is higher than the typically more-massive ALPINE survey selected to be UV-bright. The dust-obscured ratio is higher than the 61 per cent found for the typically more-massive ALPINE survey selected to be UV-bright.

\textsuperscript{5}derived using the magnification-corrected L\textsubscript{UV}/10\textsuperscript{13}L\textsubscript{⊙} = 2.28 ± 0.1 (Hashimoto et al. 2019), and the UV luminosity-to-unobscured SFR conversion factor in Madau & Dickinson (2014).

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from the method in Sommervogel et al. (2021). The observed dust temperature for A1689-zD1 is compatible with both a flattening (Liang et al. 2019; Faisst et al. 2020) and a linear (Schreiber et al. 2018) $T_d - z$ evolution. Meanwhile, the exceedingly-large scatter in $T_d$ at the highest redshifts (particularly at $z > 7$) prevents us from reaching a definitive conclusion on this observed evolution. Much of this scatter is due to observational limitations, and only through further short-wavelength observations of galaxies beyond $z > 7$ can we distinguish the possible scenarios. Part of the scatter could also be due to a larger source-to-source variation in $T_d$, which is for example seen by the large diversity of galaxies among the typically more-massive ALPINE sources (Le Fèvre et al. 2020). Such source-to-source variation can only be identified by larger unbiased samples looking at the dust-obscured star-formation at high redshift. Here, we note that an increased intrinsic scatter in dust temperature, similar to an Eddington-type bias, would significantly boost the resulting dust-obscured star-formation rate, given their strong dependence of star-formation rate on dust temperature, similar to an Eddington-type bias.

Due to the large observed faction of the SFR in A1689-zD1, one might naively expect that this galaxy also contains an exceedingly large dust mass. Instead, the dust mass derived from SED fitting might naively expect that this galaxy also contains an exceedingly large dust mass. Instead, the dust mass derived from SED fitting implies a dust yield of $y_d = 0.4^{+0.7}_{-0.1} M_\odot$ per SN. This estimate is almost an order of magnitude more accurate than the one derived without band 9 data, and most importantly, it is consistent with latest SN dust production constraints by Leśniewska & Michałowski (2019) based on the expected number of SNe given its stellar mass estimate. They find at most a $y_d = 1.1 M_\odot$ per SN, derived in the extreme case of no dust destruction/ejection. We note that SN yield is still highly debated, with other works suggesting that dust destruction processes might only spare 0.1 $M_\odot$ per SN (e.g. Matsuura et al. 2015, 2019; Slavin et al. 2020). In this extreme case, inter-stellar medium grain growth (Mancini et al. 2015; Michałowski 2015) or more exotic dust production mechanisms might well be required at $z > 7$, such as dust produced in supershells (e.g. Martínez-González, Silich & Tenorio-Tagle 2021) or in the wake of Wolf-Rayet stars (e.g. Lau et al. 2021).

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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