Estimating Dust Temperature and Far-IR Luminosity of High-Redshift Galaxies using ALMA Continuum Observations

Y. Fudamoto, A. K. Inoue, Y. Sugahara
1 Waseda Research Institute for Science and Engineering, Faculty of Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan
2 National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo, Japan
3 Department of Physics, School of Advanced Science and Engineering, Faculty of Science and Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We present a method that derives dust temperatures and infrared (IR) luminosities of high-redshift galaxies assuming the radiation equilibrium in a simple dust and stellar distribution geometry. Using public data in the Atacama Large Millimeter/submillimeter Array (ALMA) archive, we studied dust temperatures in a clumpy interstellar medium (ISM) model for high-redshift galaxies, and tested consistency of the results with what derived from other methods. We find the dust distribution model assuming clumpiness of log $\xi_{\text{clp}} = -1.02 \pm 0.41$ can represent the ISM of high-redshift star-forming galaxies. By assuming the value of $\xi_{\text{clp}}$, our method enables to derive dust temperatures and IR luminosities of high-redshift galaxies from only a single-band ALMA observation that gives two ALMA measurements required for the method: the dust continuum flux and the dust continuum emission size. Using this method, we demonstrate to find the dust temperature ($T_d = 95^{+13}_{-17}$ K) of a $z \sim 8.3$ star-forming galaxy, MACS0416-Y1. The method only requires a single-band dust observation to derive a dust temperature. It is more easily accessible than multi-band observations or emission line searches at high-redshift. Thus can be applicable to large samples of galaxies in future studies using high-resolution interferometers such as ALMA.

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

1 INTRODUCTION

Investigations of star-formation activity in the high-redshift Universe is a key to understand galaxy formation and evolution. Over the past decades, deep and wide field near infrared (NIR) surveys provided large samples of high-redshift star-forming galaxies. These surveys significantly advanced our knowledge about the history of star-formation activity of the Universe. Studies show the star-formation rate density of the Universe rapidly increases from very high-redshift to $z \sim 3$, reaches the plateau at $z \sim 3 - 2$, and decreases slowly over the last ~10 Gyr, until $z = 0$ (see Madau & Dickinson 2014 for a review).

Recently, Atacama Large Millimeter/submillimeter Array (ALMA) revolutionized our understanding of dust-obscured star formation activity at high redshift by its unprecedented sensitivity and angular resolution. ALMA's follow-up observations of rest-frame UV luminous galaxies revealed a large fraction of star-formation activities are dust-obscured even at high redshift (e.g., Fudamoto et al. 2020b; Gruppioni et al. 2020; Khusanova et al. 2021; Zavala et al. 2021; Schouws et al. 2022). In addition to these follow up observations, ALMA identified the existence of heavily dust-obscured galaxies that are too faint to be detected even in extremely sensitive rest-frame UV emission observations (e.g., Wang et al. 2019; Fudamoto et al. 2021). These studies demonstrate the importance of observational constraints on dust-obscured star-formation activities to provide a complete picture of the galaxy growth at high redshift (see Hodge & da Cunha 2020, for a review).

However, several studies pointed out that ALMA observations of infrared luminosities ($L_{\text{IR}}$) and hence dust-obscured star formation activities have large systematic uncertainties (e.g., Fudamoto et al. 2020a; Faisst et al. 2020; Sommovigo et al. 2021; Ferrara et al. 2022). The major uncertainty comes from the fact that typical ALMA observations measure fluxes at very limited widths of bands in far-infrared (FIR) wavelengths. From the limited wavelength coverage of observations, one thus typically needs to assume far infrared spectral energy distributions (FIR SEDs) to estimate total $L_{\text{IR}}$, that are obtained by integrating over the wide wavelength range of $\lambda = 8 - 1000 \mu$m.

Recent efforts start to reveal FIR SEDs of high-redshift galaxies through stacking FIR data over wide wavelength ranges (e.g., Schreiber et al. 2018; Béthermin et al. 2020), revealing that the average dust temperatures of high-redshift galaxies are much higher than those of local galaxies. Alternatively, although observations are very time consuming, several studies provide small samples of dust temperature measurements combining multi-band ALMA observations, which covers relatively wide wavelength range in the FIR (Faisst et al. 2020; Bakx et al. 2021). In addition to these direct observational constraints of FIR SEDs, combining theoretical models and observed data enabled the prediction of dust temperatures of high-redshift galaxies (e.g., Sommovigo et al. 2021; Ferrara et al. 2022).

Recently, Inoue et al. (2020) (hereafter, I20) developed an alternative and simple analytical approach that enables to derive dust temperatures and IR luminosities using single-band dust continuum...
observations, dust emission sizes, and dust-to-stellar distribution geometry models. So far, the method is applied to a few examples (I20; Sugahara et al. 2021), showing that the method constrains dust temperature of high-redshift galaxies well. In this paper, we further examined the applicability of the method developed in I20, calibrated the model using public data from the ALMA archive, and aimed to provide a simple method to derive dust temperature using single ALMA continuum measurements. We have made the code publicly available\(^1\), which is readily applicable to the upcoming ALMA’s single-band continuum observations to derive dust temperatures and IR luminosities.

This paper is organized as follows: in §2, we describe the samples and observations used in this study. In §3, we present our methodology. §4 shows results on the dust temperatures. In §5, we compare and observations used in this study. In §3, we present our methodol-

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\(^1\) https://github.com/yfudamoto/FIS22sed.git

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2 DATA

In this study, we used public data from the ALMA archive of 9 normal star-forming galaxies at \(z \sim 5.5\) to \(z \sim 8.3\) (see Table 1). We selected high-redshift (\(z > 5\)) galaxy observations that have relatively high resolution (< 1") ALMA observation showing significant dust continuum detection to measure dust emission size securely. In particular, we use galaxies that have multi-wavelength dust detections to calibrate the dust emission model (i.e., HZ4, HZ6, HZ9, HZ10, A1689-zD1, and B14-65666), and apply the calibrated model to galaxies that have only single-wavelength continuum detection to predict their dust temperatures (i.e., J2017-0208, J1211-0118, and MACS0416-Y1). We briefly describe galaxies used in this study in the following:

- HZ4 (\(z = 5.544\)), HZ6 (\(z = 5.293\)), HZ9 (\(z = 5.541\)), and HZ10 (\(z = 5.293\)) have ALMA band-6 (\(\lambda_{\text{rest}} \sim 200 \mu m\)), band-7 (\(\lambda_{\text{rest}} \sim 160 \mu m\)), and band-8 (\(\lambda_{\text{rest}} \sim 110 \mu m\)) continuum detections. Using deep multi-band ALMA observations, these galaxies have robust dust temperature measurements (Pavesi et al. 2019; Faisst et al. 2020). We use the flux density measurements from Faisst et al. (2020).

- J1211-0118 (\(z = 6.029\)) and J0217-0208 (\(z = 6.204\)) have multi-wavelength ALMA observations using band-6 (\(\lambda_{\text{rest}} \sim 200 \mu m\)), -7 (\(\lambda_{\text{rest}} \sim 160 \mu m\)), and -8 (\(\lambda_{\text{rest}} \sim 90 \mu m\)) (Harikane et al. 2020).

- A1689-zD1 (\(z = 7.13\)) is a strongly lensed galaxy having a magnification factor of \(\mu = 9.3\) (Knudsen et al. 2017). A1689-zD1 has ALMA observations using band-6 (\(\lambda_{\text{rest}} \sim 160 \mu m\)), -7 (\(\lambda_{\text{rest}} \sim 100 \mu m\)), -8 (\(\lambda_{\text{rest}} \sim 90 \mu m\)), and -9 (\(\lambda_{\text{rest}} \sim 50 \mu m\)). Using these multi-wavelength observations, A1689-zD1 has one of the most robust dust temperature constraints at \(z > 7\) (Watson et al. 2015; Knudsen et al. 2017; Bakx et al. 2021). We use the flux density measurements from Bakx et al. (2021), and the size measurement from I20.

- B14-65666 (\(z = 7.15\); also known as Big Three Dragons) shows two clumps in rest-UV and dust, suggesting an on-going merger event (Bowler et al. 2018; Hashimoto et al. 2019, 2022). B14-65666 has multi-wavelength ALMA observations using band-6 (\(\lambda_{\text{rest}} \sim 160 \mu m\)), -7 (\(\lambda_{\text{rest}} \sim 120 \mu m\)), and -8 (\(\lambda_{\text{rest}} \sim 90 \mu m\)). We treat B14-65666 as a dust-temperature constrained sample. For our analysis, we use the flux density and the size measurements from Sugahara et al. (2021).

- MACS0416-Y1 (\(z = 8.3118\)) have significant dust continuum detection using band-8 (\(\lambda_{\text{rest}} \sim 90 \mu m\); Tamura et al. 2019). However, the sensitive follow-up band-5 (\(\lambda_{\text{rest}} \sim 160 \mu m\)) observation resulted in non-detection of dust continuum. The strong lower limits of the dust temperature show extremely high dust temperature of \(T_D \gtrsim 80 \text{ K}\) (Bakx et al. 2020). We treat MACS0416-Y1 as a dust-temperature unconstrained sample. We use the flux density measurements from Bakx et al. (2021) and the size measurement from Tamura et al. (2019).

3 METHODS

3.1 Dust Geometry and Radiation Model

We use the dust emission model presented in I20, in which dust absorption and emission is treated assuming radiation equilibrium. By incorporating observed dust emission size and assuming dust geometry, the model is able to estimate dust temperature and luminosity even from single-wavelength ALMA observations.

I20 studied three different dust-to-stellar distribution model: i.e., the uniform shell, the uniform sphere, and the clumpy sphere distributions. In this study, we focus on the clumpy sphere distribution that use the analytical multi-phase medium (e.g., Neufeld 1991; Hobson & Padman 1993; Városi & Dwek 1999; Inoue 2005). We selected this model because it reflects the complicated geometry of star-forming galaxies at high redshift, more than other distribution models.

In the clumpy sphere distribution, ISM is assumed to reside in clumps and in inter-clump media. Radiation sources and clumps are then assumed to be distributed homogeneously within the inter-clump media. To describe the clumpy geometry, I20 introduced the clumpiness parameter (\(\xi_{\text{clp}}\)) that is a dimensionless, free parameter and controls the clumpiness of the system. The model can fully describe the ISM and dust geometry analytically by combining dust emission size and by the assumed clumpiness parameter (\(\xi_{\text{clp}}\)). Thus, in return, by assuming \(\xi_{\text{clp}}\) and by measuring source size, the method enable to derive dust emission, temperatures, and luminosities even using single-band dust continuum observations.

Dust emission is assumed to be optically thin modified black body radiation, typically used for high-redshift galaxies (Casey 2012), with fixed dust emissivity index (\(\beta = 2\)). Fiducial dust properties are selected based on a compilation of theoretical and empirical models and experimental measurements (see Appendix of I20): mass absorption coefficient (\(\kappa_{\text{UV}} = 5.0 \times 10^4 \text{ cm}^2 \text{ g}^{-1}\)), and dust emissivity \(\kappa_0 = 30 \text{ cm}^2 \text{ g}^{-1}\). Uncertainties of dust temperature, dust mass (IR luminosity), and geometry parameter are estimated using the Monte-Carlo technique. For more details, interested readers are referred to I20.

To use the I20 methods, one needs rest-frame UV luminosity, redshift, FIR emission size, and FIR flux, as inputs from observations. For easy running of the methods, we made two customized routines using Python: (1) to estimate dust geometry parameter (\(\xi_{\text{clp}}\)), dust temperature, and IR luminosity using multi-wavelength FIR continuum measurements (see §4.1), and (2) to estimate dust temperature
and IR luminosity assuming a dust geometry parameter using single-wavelength FIR continuum measurements (see §4.2). These codes and documentations are publicly available (see the URL in the §1).

### 3.2 Size Measurement

While most of the essential physical parameters for our sample are available from literature (see references of Table 1), dust continuum emission sizes are sometimes unavailable (HZ4, HZ6, HZ9, HZ10, J2017-0208, and J1211-0118). For these sources, we performed FIR size measurements using significantly dust continuum detected data. In particular, we performed visibility-based size measurements using the task uv_fit in the software package GILDAS\(^2\). After creating continuum visibility by masking emission lines, we used a single 2D Gaussian source model to fit the data. Free parameters of the fittings are source positions, major/minor axis FWHMs, position angles, and source fluxes. Table 1 summarizes our size measurements.

We further checked if the measured FWHMs from fitting in visibility data are consistent with those from fitting in image plane data. To measure FWHM in the image plane, we first created images using the NATURAL weighting scheme and cleaned down to 3 times RMSs, where RMSs are calculated using dirty images. Using these cleaned images, we performed 2D Gaussian fitting using CASA task IMFIT. We then found that the measured sizes match well with that measured from visibility data. For the following analysis, we use FIR sizes obtained in the visibility data.

Using the FIR size measurements, we calculated geometric means of the best fit major and minor axis FWHMs, and used them as radii of the dust continua: \( r_{\text{dust}} = \sqrt{a \cdot b / 2} \), where \( a \) is the major axis FWHM and \( b \) is the minor axis FWHM. This simplification is because I20 methods assume spherical dust emission geometry only. Further studies using more complex dust geometry is beyond the scope of this study, and will be investigated in our future work.

\(^2\) GILDAS is an interferometry data reduction and analysis software developed by Institut de Radioastronomie Millimétrique (IRAM) and is available from https://www.iram.fr/IRAMFR/GILDAS/. To convert ALMA measurement sets to GILDAS/MAPPING uv-table, we followed https://www.iram.fr/IRAMFR/ARC/documents/filler/casa-gildas.pdf

### 4 RESULTS

#### 4.1 Clumpy Medium Model Fitting using Multi-Wavelength ALMA observations

To calibrate the model ISM geometry, we measured the average value of \( \xi_{\text{clp}} \) for high-redshift galaxies. To do this, we applied the I2O method to galaxies that have multi-wavelength continuum detections in our sample.

For this step, we used HZ4, HZ6, HZ9, HZ10, A1689_zD1, and B14-65666. These galaxies have at least 3 band continuum detections in different wavelength, covering rest-frame wavelength of \( \lambda_{\text{rest}} \sim 100 \mu m \) to \( 200 \mu m \). Thus, they provide an ideal sample to calibrate the clumpiness parameter \( \xi_{\text{clp}} \) in the dust distribution geometry model. Input parameters are dust emission sizes, measured fluxes, UV luminosities, and redshift, and the routine outputs dust temperatures, dust masses, and the ISM clumpiness (\( \xi_{\text{clp}} \)). IR luminosities are calculated by the dust masses and the dust temperature. Uncertainties are estimated using the Monte-Carlo technique by fluctuating input parameters assuming Gaussian distributions. Results are listed in the Table 2 as the free \( \xi_{\text{clp}} \) sample (see Fig. A1 in the Appendix for the best fit SEDs).

Our fitting well reproduced dust temperatures and IR luminosities obtained previously in the literature. This is because this study and previous studies assume almost identical assumptions for dust emission (i.e., optically thick modified blackbody emission). By assuming a clumpy ISM geometry model and using dust emission sizes, we additionally constrained the ISM clumpiness parameter (\( \xi_{\text{clp}} \)) in this step.

We find that the average value of \( \log \xi_{\text{clp}} = -1.02 \pm 0.41 \) (Fig. 1) by an average of \( \log \xi_{\text{clp}} \) of individual galaxies where the uncertainty shows the standard deviation of individual \( \log \xi_{\text{clp}} \). We find no clear dependence of \( \xi_{\text{clp}} \) with other properties of galaxies, such as IR luminosity and dust temperature (Fig. 1). In the following analysis, we use the typical clumpiness of the model ISM geometry by assuming \( \log \xi_{\text{clp}} = -1.02 \pm 0.41 \).

#### 4.2 Applying Clumpy Medium Model using Single-Wavelength ALMA observations

By assuming ISM clumpiness obtained in the previous step, we applied our dust emission model to galaxies that have only single...
5 DISCUSSION

5.1 Uncertainty of Fixing Dust Geometry

Using high-redshift galaxies and by assuming ISM geometry, we estimated dust temperatures and IR luminosities of galaxies even when single dust emission observations are available (see §4.2). However, this is possible only when we fix dust clumpiness ($\xi_{\text{clp}}$), and we need to estimate the uncertainty introduced by fixing this parameter.

To do this, we again used galaxies with multiple dust continuum measurements (i.e., HZ4, HZ6, HZ9, HZ10, A1689-zD1, and B14-65666). We compared dust temperatures derived by fitting multiple wavelength data, and those derived assuming $\log \xi_{\text{clp}} = -1.02 \pm 0.41$ using only single dust continuum measurements. For the single-band dust temperature estimations, we used dust continuum measurements that have the highest signal to noise ratio.

Results are in Fig. 2. We found that dust temperature derived in both methods generally show one to one correspondence. However, there is a relatively large scatter and they have average distribution of $\Delta T_d = 6 \pm 11$ K that is calculated by taking average and standard deviation of $T_d$ (fixed $\xi_{\text{clp}}$) $- T_d$ (free $\xi_{\text{clp}}$) (shaded area in Fig. 2). This scatter may reflect the variation of dust geometry of individual galaxies (Fig. 1 and Tab. 2). Although the comparison shows

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Table 2. Summary of the Fitting Results

| Name        | Dust Temperature K | Dust Mass $\log (M_d/M_\odot)$ | IR Luminosity $\log (L_d/L_\odot)$ | $\log \xi_{\text{clp}}$ |
|-------------|--------------------|---------------------------------|------------------------------------|-------------------------|
| HZ4         | 59$^{+18}_{-16}$   | 7.1$^{+0.3}_{-0.2}$             | 12.2$^{+0.5}_{-0.6}$              | -1.37$^{+0.82}_{-2.33}$ |
| HZ6         | 26$^{+16}_{-4}$    | 8.4$^{+0.4}_{-0.4}$             | 11.4$^{+0.2}_{-0.1}$              | -0.19$^{+0.12}_{-0.17}$ |
| HZ9         | 41$^{+1}_{-3}$     | 7.9$^{+0.1}_{-0.1}$             | 12.1$^{+0.2}_{-0.1}$              | -1.14$^{+0.23}_{-0.16}$ |
| HZ10        | 36$^{+1}_{-2}$     | 8.5$^{+0.1}_{-0.1}$             | 12.3$^{+0.1}_{-0.1}$              | -1.02$^{+0.06}_{-0.07}$ |
| A1689-zD1   | 38$^{+1}_{-3}$     | 7.3$^{+0.1}_{-0.1}$             | 11.3$^{+0.1}_{-0.1}$              | -0.92$^{+0.14}_{-0.23}$ |
| B14-65666   | 41$^{+1}_{-3}$     | 7.4$^{+0.8}_{-0.5}$             | 11.7$^{+0.7}_{-0.3}$              | -0.44$^{+0.34}_{-0.62}$ |

* We used $\log \xi_{\text{clp}} = -1.02 \pm 0.41$ for fixed $\xi_{\text{clp}}$ objects.
5.3 Future Prospects

Although several caveats still exist in our method of estimating dust temperature and IR luminosity, it has several advantages for applying to high-redshift galaxy observations. In particular, our method only requires marginal resolution observations of dust continuum to measure its size and fluxes, which requires much shorter observational efforts compared to scanning emission lines that is sensitive to gas masses. We also encourage to study the relation between the ISM clumpiness, dust emission size, and dust temperature of lower redshift galaxies (e.g., at $z < 4$).

Our method can be applied to statistically large amount of high-redshift galaxies, which will soon become available after the deep and high-resolution survey by James Webb Space Telescope, and its follow-up observation expected by ALMA.

6 CONCLUSION

In this paper, we studied the radiation equilibrium method to estimate dust temperatures in high-redshift galaxies presented by Inoue et al. (2020), and applied it to existing observations.

We first calibrated the ISM clumpiness parameter in the dust and source distribution geometry model using galaxies that have multi-wavelength dust continuum measurements. In this step, we found that the average clumpiness parameter of $\log \xi_{clp} = -1.02 \pm 0.41$.

We then applied the method to galaxies that have only a single band detection. The single band detections give a robust dust continuum emission size, but no or very weak constraint on the dust temperature. Combining the dust continuum size measurements and a simple FIR radiation transfer model, our method successfully measured dust temperatures using single dust continuum detections.

By comparing with other methods such as multi-wavelength fittings (e.g., Bakx et al. 2020) and a [CII] line based method introduced in Sommovigo et al. (2021), we found that our method with fixing $\log \xi_{clp} = -1.02 \pm 0.41$ can estimate dust temperatures of high-redshift galaxies by showing general agreements between different methods.

Further constraining and evaluating dust geometry models require relatively high-resolution ALMA observations (i.e., < 0.5″ of beam sizes) of high-redshift galaxies that have multi-wavelength dust continuum measurements. These observations are particularly important to evaluate and reduce systematic uncertainty introduced by assuming fixed $\xi_{clp}$. Nevertheless, our method is readily able to provide estimates of dust temperatures and IR luminosities of high-redshift galaxies which only have existing and future ALMA single-band dust continuum measurements.

ACKNOWLEDGEMENTS

This paper makes use of the following ALMA data: ADS/JAO.ALMA##2018.1.00348.S, ADS/JAO.ALMA##2017.1.00908.S, ADS/JAO.ALMA##2011.1.00319.S, ADS/JAO.ALMA##2012.1.00216.S, ADS/JAO.ALMA##2013.1.01064.S, ADS/JAO.ALMA##2016.1.00954.S, ADS/JAO.ALMA##2019.1.01778.S, ADS/JAO.ALMA##2017.1.00225.S, ADS/JAO.ALMA##2016.1.00117.S, ADS/JAO.ALMA##2013.1.01064.S, ADS/JAO.ALMA##2019.1.01491.S, ADS/JAO.ALMA##2015.1.00540.S, ADS/JAO.ALMA##2016.1.00954.S, ADS/JAO.ALMA##2017.1.00190.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. YF, YS, and AKI acknowledge support from NAOJ ALMA Scientific Research Grant number 2020-16B.

**DATA AVAILABILITY**

The ALMA data presented in this paper are publicly available via the ALMA archive\(^3\). The python script used in this work is publicly distributed\(^4\).

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**APPENDIX A: SED FITS TO INDIVIDUAL GALAXIES**

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\(^3\) https://almascience.nrao.edu/aq/

\(^4\) https://github.com/yfudamoto/FIS22sed.git
Figure A1. The best fit FIR SEDs of galaxies that have multi-wavelength observations using the $\zeta_{\text{clp}}$-free clumpy ISM model (§4.1). Solid lines show median and bands show 16th to 84th percentiles of the resultant distributions. Outputs of the fittings are summarized in Tab. 2.