Big Three Dragons: A [N II] 122 μm Constraint and New Dust-continuum Detection of a z = 7.15 Bright Lyman-break Galaxy with ALMA

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Abstract

We present new Atacama Large Millimeter/submillimeter Array Band 7 observational results of a Lyman-break galaxy at z = 7.15, B14-65666 (“Big Three Dragons”), which is an object detected in [O III] 88 μm, [C II] 158 μm, and dust continuum emission during the epoch of reionization. Our targets are the [N II] 122 μm fine-structure emission line and the underlying 120 μm dust continuum. The dust continuum is detected with a ~19σ significance. From far-infrared spectral energy distribution sampled at 90, 120, and 160 μm, we obtain a best-fit dust temperature of 40 K (79 K) and an infrared luminosity of log10(LIR/L⊙) = 11.6 (12.1) at the emissivity index β = 2.0 (1.0). The [N II] 122 μm line is not detected. The 3σ upper limit of the [N II] luminosity is 8.1 × 10^3 L⊙. From the [N II], [O III], and [C II] line luminosities, we use the Cloudy photoionization code to estimate nebular parameters as functions of metallicity. If the metallicity of the galaxy is high (Z > 0.4 Z⊙), the ionization parameter and hydrogen density are log10(U) ≈ −2.7 ± 0.1 and nH ≈ 50–250 cm−3, respectively, which are comparable to those measured in low-redshift galaxies. The nitrogen-to-oxygen abundance ratio, N/O, is constrained to be subsolar. At Z < 0.4 Z⊙, the allowed U drastically increases as the assumed metallicity decreases. For high ionization parameters, the N/O constraint becomes weak. Finally, our Cloudy models predict the location of B14-65666 on the BPT diagram, thereby allowing a comparison with low-redshift galaxies.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxy formation (595); Interstellar medium (847); High-redshift galaxies (734)

1. Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA) has contributed to several pioneering works on far-infrared (FIR) fine-structure lines in star-forming galaxies at redshift z > 7, providing new insights into galaxy evolution and formation at the earliest epochs. The [C II] 158 μm emission line, one of the brightest emission lines in the FIR band, is commonly used to trace high-redshift galaxy properties (e.g., Capak et al. 2015; Camiani et al. 2018; Bakx et al. 2020; Le Fèvre et al. 2020), even at z > 7 (Maiolino et al. 2015; Pentericci et al. 2016; Hashimoto et al. 2019; Camiani et al. 2020). While the [C II] line is a dominant coolant in neutral gas (Tielens & Hollenbach 1985; Abel et al. 2005) and relevant to star-forming activities (e.g., Boselli et al. 2002; De Looze et al. 2014; Schaerer et al. 2020; Fujimoto et al. 2021), the low ionization potential of C+ (11.3 eV) permits [C II] emission in various phases: H II regions, photodissociated regions (PDRs), cold neutral and molecular medium, and shocks caused by galaxy interactions (e.g., Russell et al. 1980; Tielens & Hollenbach 1985; Appleton et al. 2013). The [O III] 88 μm is another tracer for high-redshift star formation (Inoue et al. 2014) and has also been detected at z > 7 (Inoue et al. 2016; Camiani et al. 2017; Laporte et al. 2017; Marrone et al. 2018; Hashimoto et al. 2018, 2019; Tamura et al. 2019). In contrast to the [C II] line, the [O III] line arises only from H II regions due to the high ionization potential of O^{2+} (35.1eV). The combination of these two FIR lines provides information on the physical conditions of the interstellar medium (ISM) in individual high-redshift galaxies, which are difficult to probe with weak nebular emission lines in the rest-frame ultraviolet (UV) band. Inoue et al. (2016) found a deficit in [C II]-to-[O III] luminosity ratios compared with local galaxies, possibly suggesting a highly ionized state in high-redshift galaxies. This is supported by recent observational studies (Hashimoto et al. 2019; Harikane et al. 2020; but see Carniani et al. 2020).

In addition to fine-structure lines, high-sensitivity observations with ALMA enable the detection of FIR continuum emission at z > 7 (Watson et al. 2015; Laporte et al. 2017; Hashimoto et al. 2019; Tamura et al. 2019). Infrared luminosity is dominated by thermal dust emission, reflecting UV energy absorbed by dust. Therefore, FIR spectral energy distribution (SED) is a clue for constraining dust properties, including dust temperature and dust mass. Bakx et al. (2020) reported the nondetection of dust continuum at 160 μm in a Lyman-break galaxy (LBG) at z = 8.3113, MACS0416_Y1, despite detecting it at 90 μm. These results suggest an unusually high dust temperature T_dust > 80 K or a high emissivity index β > 2. While FIR SED is usually fitted by a modified blackbody function with an assumed dust temperature, Inoue et al. (2020) proposed a new algorithm for determining dust temperature based on the radiative equilibrium of dust grains.
This paper presents new observations of an LBG, B14-65666, which is the first example of a galaxy detected in [O III] 88 μm, [C II] 158 μm, and the underlying dust continuum at the epoch of reionization (so-called “Big Three Dragons”; Hashimoto et al. 2019) in order to take a step further in understanding galaxy properties at high redshift. The new observations are used to detect another FIR emission line, [N II] 122 μm (2459.380 GHz), and the underlying dust continuum at 120 μm. An additional dust continuum measurement is useful for constraining dust properties. Observations of [N II] lines are limited at high redshift, but the number of detections has been increasing. [N II] 122 μm lines are detected in quasars at z = 2.56 (Ferkinhoff et al. 2011), 6.003 (Li et al. 2020), and 7.54 (Novak et al. 2019); a lensed dusty star-forming galaxy (DSFG) at z = 2.3 (George et al. 2014), 2.81 (Ferkinhoff et al. 2011, 2015), and 4.22 (De Breuck et al. 2019); and a submillimeter galaxy (SMG) and quasar system at z = 4.69 (Lee et al. 2019), whereas Harikane et al. (2020) reported three LBGs at z ∼ 6 that are not detected in [N II] 122 μm lines despite detecting them in [C II] and [O III] lines. In another excitation state, [N II] 205 μm lines are detected in galaxies at z = 5–6 (Pavesi et al. 2016), SMGs at 3 < z < 6 (Cunningham et al. 2020), and z > 4 objects, including quasars and DSFGs (e.g., Decarli et al. 2014; De Breuck et al. 2019; Novak et al. 2019; Cheng et al. 2020).

It is important to study the galaxy ISM with emission-line diagnostics through a wide range of redshifts at z = 0–7. At z = 0–2, physical properties in star-forming galaxies are probed in detail using rest-frame optical emission lines. The optical wavelength range includes emission lines from different elements (e.g., H, O, N, S), excited states (e.g., [N II] λ6549,6585), and ionization states (e.g., O+ and O2+); thus, temperatures, densities, elemental abundances, and ionizing sources in H II regions can be inferred by comparing emission-line fluxes. The nitrogen-to-oxygen (N/O) abundance ratio provides a clue to the chemical evolution in galaxies (e.g., Vincenzo et al. 2016) because more nitrogen is produced through the carbon–nitrogen–oxygen (CNO) cycle as a secondary nucleosynthesis product in stars with higher metallicity. Among dominant ionizing sources of strong line emitters, star formation and active galactic nuclei (AGNs) can be distinguished on the [O III]–Hβ–[N II]–Hα plane, the so-called Baldwin–Phillips–Terlevich (BPT) diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). The distribution on the BPT diagram is theoretically interpreted as a combination of the nebular physical parameters and hardness of ionizing radiation (Kewley et al. 2013).

Galaxy properties at z = 2 have been explored using near-infrared (NIR) instruments to detect redshifted optical lines. On the BPT diagram, the sequence of star-forming galaxies at z ∼ 2 has an offset from the local sequence (e.g., Shapley et al. 2005; Erb et al. 2006), which is statistically confirmed using the KBSS-MOSFIRE sample (Steidel et al. 2014, 2016; Strom et al. 2017), the MOSDEF sample (Shapley et al. 2015; Sanders et al. 2016; Shivaei et al. 2018), and Subaru/FMOS observations (Yabe et al. 2014; Hayashi et al. 2015; Kashino et al. 2017). This offset on the BPT diagram originates from the redshift evolution of ionization states in star-forming galaxies. Strom et al. (2018) derived the N/O abundance ratios of KBSS-MOSFIRE galaxies to find that the N/O ratio at z ∼ 2 is comparable with local abundance ratios (Pilyugin et al. 2012) at fixed metallicities even though an increase in the N/O ratio is suggested from local to z ∼ 2 in some studies (e.g., Masters et al. 2014; Sanders et al. 2016; Kojima et al. 2017).

The optical and NIR observations are powerful tools for galaxy properties, but a redshift range is limited from z ∼ 0 to 2. We have to wait for FIR observations with the James Webb Space Telescope (JWST) to extend the studies for higher redshifts. On the other hand, few galaxies are detected in FIR fine-structure lines including [O III] 88 μm at 0 < z < 3 (e.g., Ferkinhoff et al. 2010; Zhang et al. 2018), because FIR observations of fine-structure lines are mainly available for galaxies at z ≥ 2–3 using ALMA or for local galaxies using telescopes such as Herschel, ISO, AKARI, and SOFIA. This redshift gap in FIR observations makes it difficult to discuss a continuous galaxy evolution scenario. We propose comparisons of the physical ISM properties at various redshifts estimated from either FIR or optical emission lines to overcome this difficulty, with the aid of a photoionization model.

This paper consists of the following sections. Section 2 describes the B14-65666 observations and data reduction process. Section 3 presents the dust continuum and [N II] 122 μm emission-line measurements. Section 4 explains FIR SED fittings and their results. We evaluate nebular parameters from [O III] 88 μm and [C II] 158 μm in Section 5. We discuss the N/O abundance ratio and BPT diagram at z ∼ 7 using these nebular parameters. Section 6 summarizes our findings.

### 2. Observation and Data Reduction

Our target object, B14-65666, is located at R.A. 10° 01′ 40′′ 69′′, decl. +01°54′52″42″ (J2000). It was found by Bowler et al. (2014) and spectroscopically detected in Lyα by Furusawa et al. (2016). Bowler et al. (2018) performed ALMA follow-up observations with Band 6 in Cycle 3 and reported the detection of a 160 μm dust continuum. Hashimoto et al. (2019) detected [O III] 88 μm, [C II] 158 μm, and underlying dust continua in Cycles 4 and 5.

We target the [N II] 122 μm emission line, which is free from strong atmospheric absorption, to obtain a signature of nitrogen. The frequency (wavelength) of the line at the rest frame is 2459.380 GHz (121.898 μm). An advantage of this line is that it has a similar critical density to the [O III] 88 μm (238 and 500 cm−3 at 104 K, respectively), resulting in a weak dependence of the [N II] 122 μm/[O III] 88 μm line ratio on electron density. In contrast, the [N II] 205 μm line has a lower critical density (38 cm−3) by an order of magnitude than the [O III] line, leading to a quick drop of the [N II]-to-[O III] line ratio at high density. The [N II] 57 μm line is another candidate observable with Band 9. Because N2+ has a similar ionization potential to O2+, [N II]-to-[O III] line ratios do not depend on the ionization parameter as strongly as [N II]-to-[O III] ratios, but it takes a longer integration time to detect the [N II] 57 μm line with the same significance level as the [N II] 122 μm line.

We have observed B14-65666 in 2019 November with ALMA Band 7 during Cycle 7 (ID: 2019.1.01491.S, PI: A. K. Inoue). The 12 m array was configured in the C43-2

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11 This is taken from the Spectral Line Atlas of Interstellar Molecules (SLAIM) (available at http://www.splatalogue.net; F. J. Lovas, private communication, Remijan et al. 2007).

12 In this paper, the critical density for a given excited state is defined as the density at which the sum of collisional excitation and deexcitation rates balances the spontaneous emission rate. Critical densities are computed using PyNeb (Luridiana et al. 2015).
configuration. The correlator was operated in a time division mode with 2.000 GHz bandwidths and 31.2 MHz spectral resolution. One of the four spectral windows targets the [N II] 122 μm emission line at an expected frequency of 301.6885 GHz, and the others target dust continuum emission at 299.893, 289.500, and 287.700 GHz. The total on-source exposure time was 143 minutes. The bandpass/flux calibrators are quasars J1058+0133 and J0725-0054. The phase calibrator is J1010-0200.

Data reduction and calibration are performed using a standard pipeline on Common Astronomy Software Applications (CASA; McMullin et al. 2007) version 5.6.1-8. A dust continuum image is created using a CASA task tclean with natural weighting. A line cube is created using tclean with a ∼15.6 km s⁻¹ spectral resolution after the dust continuum is subtracted with a CASA task uvccontsub. In both the dust continuum image and line momentum 0 map (Section 3.2), the beam size is approximately 1.15 × 0.97, and the beam position angle is approximately 73°.

3. Measurements

3.1. 120 μm Dust Continuum Emission

The left panel of Figure 1 illustrates the 120 μm dust continuum image with white contours overlaid on the F140W-band image taken using the Wide Field Camera 3 (WFC3) on board the Hubble Space Telescope (HST). The rms of the image is σ = 9.8 μJy beam⁻¹. The dust continuum is significantly detected with a peak signal-to-noise ratio (S/N) of 18.9. This detection makes B14-65666 the second object in which dust continua are detected in more than two bands at z > 7 after A1689zD1 (Watson et al. 2015; Knudsen et al. 2017; Inoue et al. 2020). Bowler et al. (2018) suggested a physical offset of 3 kpc between the dust continuum and UV emission, but our measurement of 120 μm dust emission shows no spatial offset from UV emission on the WFC3/F140W image, which has consistent astrometry with the images used by Bowler et al. (2018). Although the 120 μm dust emission is not spatially resolved with this beam size, our result that no spatial offset was observed is consistent with the results on the 90 and 160 μm dust continua reported by Hashimoto et al. (2019).

90 μm flux density [μJy] = 470 ± 128
120 μm flux density [μJy] = 218 ± 19
160 μm flux density [μJy] = 130 ± 25

We measure the spatially integrated flux density of the dust continuum using a 2D Gaussian profile with a CASA task imfit. The measured flux density is 218 ± 19 μJy. This flux density at 120 μm is less than the continuum flux density at 90 μm (470 ± 128 μJy) but larger than at 160 μm (130 ± 25 μJy), measured in Hashimoto et al. (2019). The 120 μm flux density has a higher S/N than the 90 and 160 μm flux density by a factor of 3–4. These measurements are listed in Table 1. We examine the FIR SED with modified blackbody and radiative equilibrium models to estimate the IR luminosity based on Inoue et al. (2020) in Section 4.

### Table 1

A Summary of Measurements of B14-65666

| Parameters                  | Measurements | References |
|-----------------------------|--------------|------------|
| [N II] flux [Jy km s⁻¹]     | <0.0514      | This study |
| [O III] flux [Jy km s⁻¹]    | 1.5 ± 0.18   | H19        |
| [C II] flux [Jy km s⁻¹]     | 0.87 ± 0.11  | H19        |
| [N II] luminosity [L_*]     | < 8.1 × 10⁷  | This study |
| [O III] luminosity [L_*]    | (3.4 ± 0.4) × 10⁶ | H19 |
| [C II] luminosity [L_*]     | (1.1 ± 0.1) × 10⁶ | H19 |
| 90 μm flux density [μJy]    | 470 ± 128    | H19        |
| 120 μm flux density [μJy]   | 218 ± 19     | This study |
| 160 μm flux density [μJy]   | 130 ± 25     | H19        |

Note. The measurements taken from H19 represent total values, meaning the whole emission from two clumps.

References—H19: Hashimoto et al. (2019).

3.2. Upper Limit of the [N II] 122 μm Emission Line

We expect that the redshift of [N II] emission lines will be the same as the redshift of [O III] emission lines because both of them, which have higher ionization potentials than hydrogen, will arise from H II regions. We assume the observed-frame [N II] 122 μm frequency to be 301.7 GHz (993.7 μm) using a systemic redshift of z = 7.1521, which was determined from
the [O III] 88 μm and [C II] 158 μm emission lines by Hashimoto et al. (2019).

We find no emission-line features around the observed-frame [N II] frequency. Assuming that the [N II] line width is ≳400 km s^{-1}, which is close to the FWHM of the [C II] and [O III] lines (Hashimoto et al. 2019), we create a [N II] flux (moment 0) map integrated from −201 to 203 km s^{-1} around the observed-frame [N II] frequency with a CASA task imoments, excluding channels at −139 to −61 km s^{-1} that are noisy through weak atmospheric absorption. In the right panel of Figure 1, the contours illustrate the [N II] flux map. Figure 2 shows a spatially integrated spectrum in a 1" radius aperture around the galaxy. The noise spectrum shown by the dotted lines is measured by placing 500 random apertures of the same radii. There is no significant detection with \(S/N > 3\) in the image and spectrum.

An upper limit of the [N II] line emission is measured from the uncertainty of the flux map. The rms of the [N II] flux map is 17.1 mJy beam^{-1} km s^{-1}. Given the source size of the HST image, the galaxy will not be resolved spatially. Therefore, the 3σ upper limit of the [N II] flux is computed from the rms in the flux map to be 51.4 mJy km s^{-1}, by adopting the spatial size of a single beam. The line flux limit is converted to the line-luminosity limit using the luminosity distance and observed frequency (Carilli & Walter 2013). The [N II] line luminosity is constrained to be \(8.1 \times 10^{7} L_{\odot}\) as the 3σ upper limit. The [N II] line flux and luminosity are listed in Table 1, as well as the [O III] and [C II] lines taken from Hashimoto et al. (2019).

The constraint of [N II] line luminosity is lower than the measurements for star-forming/starburst galaxies in literature. Lee et al. (2019) detected an [N II] 122 μm line in the BRI 1202-0725 SMG at \(z = 4.96\) and obtained the line luminosity of \(2.71 \pm 0.65 \times 10^{8} L_{\odot}\). The [N II] line luminosity of SPT 0418-563 at \(z = 4.2\) measured by De Breuck et al. (2019) is \(1.6 \pm 0.5 \times 10^{9} L_{\odot}\), which is corrected with the gravitational magnification factor of \(\mu = 32.7\) (Spilker et al. 2016). SMMJ02399-0136 and the Cosmic Eyelash, lensed DSFGs at \(z = 2-3\), exhibit the lens-corrected [N II] line luminosities of \(2.0 \pm 0.3 \times 10^{10} L_{\odot}\) (Ferkhlinhoff et al. 2015) and \(5.2 \pm 0.5 \times 10^{8} L_{\odot}\) (Zhang et al. 2018), respectively. Harikane et al. (2020) observed three LBGs at \(z \sim 6\) with ALMA but did not detect the [N II] line for any of the three objects, while they did detect [O III] 88 μm and [C II] 158 μm lines. The [N II] luminosities of these objects are \(< 6.2 \times 10^{8}, < 8.3 \times 10^{8}\), and \(< 1.2 \times 10^{9} L_{\odot}\) for the upper limits, which are integrated in 600 km s^{-1} velocity width and a 2" aperture. Our upper limit of [N II] luminosity is several times lower than these constraints in the literature despite the higher redshift of B14-65666.

4. FIR SED Fitting

4.1. Modified Blackbody Fitting

We perform FIR SED fitting to estimate the IR luminosity and dust mass by combining the new 120 μm dust continuum emission with previous measurements of the 90 and 160 μm dust continua underlying [O III] 88 μm and [C II] 158 μm. In this paper, we only discuss the total FIR SED, assuming a constant dust temperature in the entire system of B14-65666, while the galaxy is composed of two components and is suggested to be a merging system (Hashimoto et al. 2019). First, we fit a standard modified blackbody function to the observed FIR flux densities:

\[ F_\nu^{\text{obs}} = \frac{1 + z}{d_L^2} M_\text{d} \kappa_\nu \left( B_\nu(T_\text{d}) - B_\nu(T_{\text{CMB}}) \right), \]

where \(z\) is the source redshift and \(d_L\) is the luminosity distance. \(M_\text{d}\) is the dust mass, which is the normalization of the equation. \(\kappa_\nu\) is the dust emissivity at the frequency \(\nu\). \(B_\nu(T)\) is the blackbody function, and \(T_\text{d}\) is the dust temperature of the source. \(T_{\text{CMB}}\) is the cosmic microwave background (CMB) temperature at the source redshift, and \(B_\nu(T_{\text{CMB}})\) denotes CMB intensity. The negative \(\ln B_\nu(T_{\text{CMB}})\) term accounts for a correction of the CMB effect in interferometric observations (da Cunha et al. 2013).

Although assumptions on the emissivity value systematically affect estimates of dust mass (e.g., Fanciullo et al. 2020), there are large variations among empirical estimates, theoretical models, and laboratory measurements of emissivity as briefly reviewed in Inoue et al. (2020). Following Inoue et al. (2020), we assume a typical value of \(\kappa_\nu = 30 \text{ cm}^2 \text{ g}^{-1}(100 \mu\text{m}/\lambda)^\beta\) with the wavelength \(\lambda = c/\nu\) and the light speed \(c\) and the emissivity index \(\beta = 1.0, 1.5, \text{ or } 2.0\). The pivot value of \(30 \text{ cm}^2 \text{ g}^{-1}\) at 100 μm is very similar to that of astronomical silicate (Draine & Lee 1984; Weingartner & Draine 2001) and the THMIS model (Jones et al. 2017). Figure 3 shows the results obtained from the least-\(\chi^2\) fitting with two free parameters of \(M_\text{d}\) and \(T_\text{d}\). There is a degeneracy between \(M_\text{d}\) and \(T_\text{d}\) because we do not constrain the peak of FIR SED yet. A data point at a shorter wavelength than 90 μm is important to break this degeneracy. The best-fit \(T_\text{d}\) spans 80 K to 40 K and is lower for a larger \(\beta\). The best-fit \(\ln T_\text{d}/(M_\text{d}/M_\odot)\) increases from 6.6 to 7.5 with increasing \(\beta\). The corresponding total IR luminosity changes from \(\ln L_{\text{IR}}/(L_\odot) = 12.0\) to 11.6. The obtained values and their uncertainties are listed in Table A1 in the Appendix. Although we find the smallest \(\chi^2\) value for \(\beta = 1.0\), \(\chi^2\) differences compared to \(\beta = 1.5 \text{ or } 2.0\) are not statistically significant.

4.2. Radiative Equilibrium Fitting

Inoue et al. (2020) presented a new algorithm to derive dust temperature and mass using radiative equilibrium on dust grains. Radiative equilibrium connects \(T_\text{d}\) with \(M_\text{d}\) and breaks the degeneracy between them. Therefore, we may obtain tighter constraints on them even without observing the FIR SED peak.
The algorithm requires the observed UV luminosity, \( L_{\text{UV}} \), and the physical radius of the system, \( R \). We adopt values taken from Hashimoto et al. (2019). The total UV luminosity is \( L_{\text{UV}} = (7.6 \pm 1.3) \times 10^{44} \text{ erg s}^{-1} \). The observed FWHMs along the major and minor axes of the entire dust emission in Band 6 are \( a = 3.8 \pm 1.1 \text{ kpc} \) and \( b = 0.8 \pm 0.5 \text{ kpc} \) in the proper coordinate, respectively. The Band 6 observation in Hashimoto et al. has a higher spatial resolution than our Band 7 observation. Assuming a spherically symmetric structure for the analytic treatment of Inoue et al. (2020), we adopt the radius of \( R = \sqrt{ab}/2 = 0.87 \pm 0.30 \text{ kpc} \).

Following Inoue et al. (2020), we perform least-\( \chi^2 \) fitting for FIR SED with the radiative equilibrium algorithm in three geometries: spherical shell, homogeneous sphere, and clumpy sphere. The spherical shell and homogeneous sphere geometries require only a single free parameter, \( M_d \) (or \( T_d \)), and the other quantity of \( T_d \) (or \( M_d \)) is derived from \( M_d \) (or \( T_d \)) thanks to the radiative equilibrium. The clumpy geometry requires an additional free parameter to control the clumpiness, \( \xi_{cl} \), which is a nondimensional parameter defined by the ratio between a single clump size relative to the entire system size and the volume-filling factor of the clumps. Figure 4 shows the fitting results for the case of \( \beta = 2.0 \). The other two \( \beta \) cases are shown in the Appendix. Figure 11. Radiative equilibrium requires the relations between \( T_d \) and \( M_d \) shown by the short-dashed, long-dashed, and dotted lines for the shell, homogeneous, and clumpy geometries, respectively. We consider the uncertainties of \( L_{\text{UV}} \) and \( R \) in addition to FIR flux densities in the fitting using a Monte Carlo method (Inoue et al. 2020). Therefore, the resultant uncertainties in \( M_d \) and \( T_d \) are still large. The clumpy geometry case gives the same best-fit solutions as those of the modified blackbody fitting because the clumpiness parameter functions as an adjuster (Inoue et al. 2020). Figure 5 shows the best-fit FIR SEDs for \( \beta = 2.0 \), and Figure 6 shows the distribution of the solutions in the \( M_d \) and \( \xi_{cl} \) plane for \( \beta = 2.0 \). Other \( \beta \) cases are found in Figures 12 and 13, respectively. The numerical values are summarized in the Appendix, Table A1. For the shell and homogeneous geometries, the cases of \( \beta = 1.5 \) and 2.0 result in larger \( \chi^2 \) values and are not favored statistically compared to the case of \( \beta = 1.0 \). For the clumpy geometry, all \( \beta \) cases cannot be regarded to be different statistically.

The best-fit \( T_d \) values are \( \approx 100 \text{ K} \) in the shell geometry, 80–100 K in the homogeneous geometry, and 40–80 K in the clumpy geometry. The corresponding \( \log_{10}(M_d/M_\odot) \) values are 6.4–6.6, 6.5–6.7, and 6.6–7.5, respectively. The IR luminosities are \( \log_{10}(L_{IR}/L_\odot) = 12.5–13.0, 12.4–12.6, \) and 11.6–12.1, respectively. Comparing our results for B14-65666 to those for another z \( \approx 7 \) DSFG, A1689zD1 (Inoue et al. 2020), we find some similarities in the dust properties of those high-redshift objects. In the shell and homogeneous geometries, both objects exhibit high IR luminosities and corresponding high SFRs, possibly indicating the invalidity of these simple geometries. Hereafter, we adopt the case of the clumpy geometry at \( \beta = 2.0 \) for the IR luminosity as the fiducial case.

In the clumpy geometry, the best-fit clumpiness parameter is \( \xi_{cl} = 0.1–0.4 \) for B14-65666, which is similar to that for A1689zD1. As discussed in Inoue et al. (2020), if a clump size is similar to the size of giant molecular clouds of \( \sim 10 \text{ pc} \) in the local universe (Larson 1981; Fukui et al. 2008), these values correspond to a clump volume-filling factor of 3%–10%. Although observing such tiny clouds is difficult without significant gravitational lensing, a comparison between the clumpiness expected from the radiative equilibrium algorithm and galaxy formation simulations will be interesting.

5. Discussion

5.1. Ratio of [N II] to IR Luminosity

In Figure 7, we compare the ratio of the [N II] 122 \( \mu \text{m} \) to IR luminosity \( (L_{\text{N II}}/L_IR) \) with the ratios in the literature. The observed line-to-IR luminosity ratio decreases with increasing IR luminosity in local luminous infrared galaxies (line deficit; e.g., Herrera-Camus et al. 2018a, 2018b). Figure 7 shows \( L_{\text{N II}}/L_IR \) as a function of \( L_IR \). The three red circles show the measurements of this study, reflecting the uncertainties of the IR luminosity in the clumpy geometry. The gray open symbols depict the local reference measurements: dwarf galaxies (Madden et al. 2013; Cormier et al. 2015), ultra/luminous infrared galaxies (Farrah et al. 2013), and star-forming, Seyfert, and luminous infrared galaxies (Herrera-Camus et al. 2018b). The \( L_{\text{N II}}/L_IR \) upper limits of B14-65666 are on the relation of the local galaxies. At high redshift, SPT 0418-47 exhibits a [N II] luminosity consistent with the local galaxies (De Breuck et al. 2019). In contrast, some

\[ \chi \]
demonstrates that \( B14-65666 \) does not show an excess in the temperature short-dashed, green long-dashed, and blue dotted lines show the dust homogeneous, and clumpy models, respectively. The black cross represents the best-fit solution in the modified blackbody case. The dotted–dashed line shows the dust temperature–mass relation of the observed Band 7 flux density. The red short-dashed, green long-dashed, and blue dotted lines show the dust temperature–mass relations in the radiative equilibrium for the shell, homogeneous, and clumpy models, respectively.

Figure 4. Best-fit solutions (symbols) and 68% areas (solid lines) in the radiative equilibrium fitting, and the dust temperature and mass plane for the emissivity index \( \beta = 2.0 \). The red triangle, green square, and blue diamond represent the best-fit solutions in the shell, homogeneous, and clumpy geometries, respectively. The black cross represents the best-fit solution in the modified blackbody case. The dotted–dashed line shows the dust temperature–mass relation of the observed Band 7 flux density. The red short-dashed, green long-dashed, and blue dotted lines show the dust temperature–mass relations in the radiative equilibrium for the shell, homogeneous, and clumpy models, respectively.

Figure 5. Best-fit FIR SEDs for the shell (red), homogeneous (green), and clumpy (blue) models. The data points with error bars are ALMA measurements. The emissivity index is \( \beta = 2.0 \).

high-redshift objects are located above the local relations, like SMMJ02399-0136 (Ferkinhoff et al. 2011, 2015), the Cosmic Eyelash (George et al. 2014; Zhang et al. 2018), BRI 1202-0725 SMG (Iono et al. 2006; Lee et al. 2019), and \( z > 2 \) quasars (Ferkinhoff et al. 2015; Lee et al. 2019; Li et al. 2020; Novak et al. 2019) as discussed in Li et al. (2020). Our analysis demonstrates that \( B14-65666 \) does not show an excess in the \([\text{N II}]-\text{IR} \) luminosity ratio from the local decreasing trend.

Compared with the upper limits of \( \sim 1-3.6 \) lensed DSFGs (Zhang et al. 2018) and \( z \sim 6 \) LBGs (Harikane et al. 2020), our observation gave stringent upper limits of \( L_{\text{[N II]}22}/L_{\text{IR}} \) for \( B14-65666 \) at a fixed \( L_{\text{IR}} \).

5.2. Estimates of Nebular Physical Parameters

Emission-line ratios originating from star-forming activities are determined by the physical properties of nebulae around massive stars. Given nebular parameters and ionizing radiation sources, photoionization models of the nebulae can be constructed, and the emission-line fluxes from various atoms and ions can be predicted. In this section, we use a photoionization code Cloudy (Ferland et al. 1998) to examine principal nebular parameters, i.e., the metallicity \( Z \), ionization parameter \( U \), and hydrogen density \( n_H \) at a surface illuminated by an ionizing radiation source.

The luminosities of the \([\text{O III}] \) 88 \( \mu \text{m} \) \( L_{\text{O III}88} \) and \([\text{C II}] \) 158 \( \mu \text{m} \) \( L_{\text{C II}158} \) lines provide information on the nebular parameters. We use the \( L_{\text{O III}88}/L_{\text{H}\alpha} - L_{\text{C II}158}/L_{\text{H}\alpha} \) diagram, similar to the \( L_{\text{O III}88}/\text{SFR} - L_{\text{C II}158}/\text{SFR} \) diagram proposed by Harikane et al. (2020), to estimate the nebular parameters. Harikane et al. illustrated a diagram that compared \( L_{\text{O III}88}/\text{SFR} \) and \( L_{\text{C II}158}/\text{SFR} \) as functions of \( U \), \( n_{\text{H}} \), \( Z \), and other parameters. We adopt the concepts of Harikane et al. and Nagao et al. (2011, 2012) to model H II regions and PDRs in a plane-parallel geometry using a software Cloudy version 17.01 (Ferland et al. 2017) under the assumptions of pressure equilibrium, identical metallicity in the stellar and gas phases, and solar C/O abundance. Following Inoue et al. (2014), in our model, we use input spectral shapes of 10 Myr constant star formation models at stellar metallicities of \( Z_{\odot} = 0.02, 0.2, 0.4 \), and 1.0 \( Z_{\odot} \), created with STARBURST99 (Leitherer et al. 1999) with a Salpeter initial mass function at 1–100 \( M_{\odot} \). We also test
other input spectral shapes created with the Binary Population and Spectral Synthesis code (BPASS; Eldridge et al. 2017) version 2.2.1 (Stanway & Eldridge 2018) to find that the results are qualitatively the same and that our conclusions do not change. Parameter grids of $U$ and $n_H$ are $-4.0 < \log_{10} U < -0.5$ and $0 < \log_{10} n_H / \text{cm}^{-3} < 4.0$ in steps of 0.25 dex. The software is run until the V-band dust extinction reaches 100 mag (Abel et al. 2005). Cloudy outputs emission-line strengths relative to an H β line. From the [O III] 88 μm/H β, [C II] 158 μm/H β, and Hα/H β line ratios, we computed [O III]/Hα and [C II]/Hα line ratios, that is, $L_{[O \text{ III}]} / L_{H\alpha}$ and $L_{[C \text{ II}]} / L_{H\alpha}$, luminosity ratios.

The free parameters in our model are $U$, $n_H$, $Z$, and the PDR covering fraction $C_{\text{PDR}}$. $C_{\text{PDR}}$ is a posterior parameter described in Cormier et al. (2019) and Harikane et al. (2020), regulating line intensities emitted from the PDR. Geometrically, it means what fraction of a surface of a H II region is covered by a PDR: the H II region is entirely covered by the PDR when $C_{\text{PDR}} = 1$, while part of the H II region is not covered for a low-$C_{\text{PDR}}$ case and thus [C II] line intensities from the PDR are scaled by a factor of $C_{\text{PDR}}$. When $Z$ and $C_{\text{PDR}}$ are fixed, a nebular parameter pair ($U$, $n_H$) is in one-to-one correspondence with ($L_{[O \text{ III}]} / L_{H\alpha}$, $L_{[C \text{ II}]} / L_{H\alpha}$), as shown in the top panel of Figure 8. We derive $U$ and $n_H$ as functions of $Z$, for $C_{\text{PDR}} = 1.0$ and 0.1 as fiducial parameters.

The SFR and gas-phase metallicity of B14-65666 are almost constrained to be $\text{SFR} = 200^{+82}_{-38} \ M_{\odot} \ yr^{-1}$ and $Z = 0.4^{+0.4}_{-0.2} \ Z_{\odot}$ using SED fitting in Hashimoto et al. (2019). SED fitting uses photometry from NIR to ALMA FIR bands (from UV to FIR bands in the rest frame), including the effect of dust attenuation. The estimated metallicity is consistent with other metallicity estimates from the [O III] 88 μm luminosity and SFR by Jones et al. (2020). Compared to the errors of $\approx 12\%$ in
$L_{\text{O III}}$ and $L_{\text{C II}}$, the SFR error is large and dominates measurement uncertainties in the results. We, therefore, evaluate uncertainties in the nebular parameters using SFR = 162, 200, and 282 $M_\odot$ yr$^{-1}$ at metallicities from $Z = 0.2$ to 0.8 $Z_\odot$. We obtain $L_{\text{O III}}/L_{\text{H}}$ and $L_{\text{C II}}/L_{\text{H}}$ ratios for B14-65666 by computing $L_{\text{H}}$, from the SED SFR using Equation (2) in Kennicutt (1998) with a correction factor of 0.63 (Madau & Dickinson 2014) from Salpeter (1955) to Chandrier (2003) initial mass functions. At each metallicity, ($L_{\text{O III}}/L_{\text{H}}$, $L_{\text{C II}}/L_{\text{H}}$) values can be converted into ($U$, $n_\text{H}$) values through linear interpolation. Figure 8 displays the $L_{\text{O III}}/L_{\text{H}}$, $L_{\text{C II}}/L_{\text{H}}$ diagram at $Z = 0.4$ $Z_\odot$ and $C_{\text{PDR}} = 1.0$. The model grid in the diagram depends on the $Z$ and $C_{\text{PDR}}$ values. The modeled $L_{\text{O III}}/L_{\text{H}}$, $L_{\text{C II}}/L_{\text{H}}$ values increase with an increase in metallicity due to high oxygen abundances, whereas the modeled $L_{\text{C II}}/L_{\text{H}}$, $L_{\text{C II}}/L_{\text{H}}$ values decrease with a decrease in $C_{\text{PDR}}$ by almost the same factor. We refer readers to Harikane et al. (2020) for detailed characteristics of the models.

The bottom panel of Figure 8 shows the estimated $U$ values as a function of $Z$, color-coded by $n_{\text{H}}$. The triangles, circles, and upside-down triangles show the low (162), middle (200), and high (282 $M_\odot$ yr$^{-1}$) SFR cases for $C_{\text{PDR}} = 1.0$, respectively. $U$ and $n_{\text{H}}$ monotonically decrease and increase at a fixed SFR, respectively, as the assumed metallicity increases. At high metallicities of $Z > 0.4$ $Z_\odot$, the ionization parameter is almost constant at $\log_{10} U \sim -2.7 \pm 0.1$ and the hydrogen density is $n_{\text{H}} \sim 50-250$ cm$^{-3}$. The dispersion of $U$ caused by the SFR uncertainty is small. The $U$ values are comparable with those in local dwarf (Cormier et al. 2019) and $z \sim 2$ galaxies (Strom et al. 2018) in a similar metallicity range, as well as nearby starburst galaxies with higher metallicity (Herrera-Camus et al. 2018a). Specifically, these $U$ values are on $U-Z$ invariant relation from local to $z \sim 2$ galaxies (Sanders et al. 2020). The range of the hydrogen density of our galaxy is between the average values of local and $z \sim 2$ galaxies (Sanders et al. 2016). We do not find any further increase of hydrogen density from $z \sim 2$ to 7 even though hydrogen density increases with an increase in redshift by a factor of 10 from $z \sim 0$ to 2 galaxies (e.g., Sanders et al. 2016). In contrast, at $Z < 0.4$ $Z_\odot$, $\log_{10} U$ drastically increases up to $-1.0$ with a decrease in metallicity. Hydrogen density simultaneously drops to $n_{\text{H}} \sim 1$ cm$^{-3}$. Such extreme conditions of the nebular parameters are hardly found in normal galaxies at low redshifts, whereas dwarf galaxies with low metallicity and low specific SFR tend to exhibit similar high $U$ and low $n_{\text{H}}$ (Cormier et al. 2019). These drastic changes in the nebular parameters are caused by the high $L_{\text{O III}}/L_{\text{H}}$ ratio (i.e., high $L_{\text{O III}}/L_{\text{SFR}}$ of B14-65666, which is difficult to explain in low-metallicity regimes in our model. Notably, our model cannot reproduce the high $L_{\text{O III}}/L_{\text{H}}$ ratio at $Z < 0.1$ $Z_\odot$ even in the high-SFR case. The crosses in Figure 8 depict the models at $C_{\text{PDR}} = 0.1$. In this case, $U$ and $n_{\text{H}}$ become smaller than the $C_{\text{PDR}} = 1.0$ case at a fixed metallicity. Specifically, $n_{\text{H}}$ is predicted to be low; the values are smaller by an order of magnitude at $Z > 0.4$ $Z_\odot$ and $n_{\text{H}} \lesssim 10$ cm$^{-3}$ at $Z < 0.4$ $Z_\odot$. However, qualitative tendencies of $U$ and $n_{\text{H}}$ to $Z$ are unaffected by the $C_{\text{PDR}}$ difference.

It is informative to compare our photoionization models with previous works focusing on [O III] and [N II] lines. Rigopoulou et al. (2018) used the ionization models in Pereira-Santaella et al. (2017) to estimate gaseous metallicity from a line ratio of [O III] 88 $\mu$m to [N II] 122 $\mu$m ([O III]/[N II]), under the assumption of a local N/O–Z relation. The [O III]/[N II] ratio is insensitive to hydrogen density but sensitive to the metallicity and ionization parameter (Pereira-Santaella et al. 2017). Rigopoulou et al. first inferred the ionization parameter from 88- to 122- $\mu$m dust continuum ratios and then derived the metallicity from the ionization parameter and [O III]/[N II] ratio. The dust continuum ratio of B14-65666 is 1.4–2.9 (Table 1), corresponding to $\log_{10} U \sim -1$ at $n_{\text{H}} = 100$ cm$^{-3}$, which is higher than our model predictions on average. Our measurement of [O III]/[N II] $\geq 40$ for B14-65666 gives a weak metallicity constraint of $Z \lesssim 1$ $Z_\odot$ for $\log_{10} U \sim -2$ (the highest ionization parameter value in Pereira-Santaella et al. model) and a marginal constraint of $Z \lesssim 0.6$ $Z_\odot$ for $\log_{10} U \sim -2.7$, which is consistent with the metallicity range estimated from the SED fitting (Hashimoto et al. 2019). The reason for the high ionization parameter inferred from the 88- to 122- $\mu$m dust continuum ratio is unclear, but it may be related to the fact that high-redshift galaxies tend to exhibit higher dust temperatures (Bakx et al. 2020) than local galaxies that were used for their model calibration.

Although we assume that [C II] emission is emitted from H II regions and PDRs, [C II] emission also arises from shock excitation caused by galaxy interactions. It can be a cause for concern that shocks contribute to the [C II] line flux as B14-65666 exhibits a merger morphology (Hashimoto et al. 2019). Appleton et al. (2013) measured the [C II] flux originating from shocks by observing the intergalactic medium in Stephan’s Quintet. They report that the [C II]/IR luminosity ratios are $>10^{-1.5}$, which is higher than those measured in star-forming galaxies, including B14-65666 ($>10^{-2.5}$; Hashimoto et al. 2019). The [C II] luminosity by shocks ($>10^7 L_\odot$) is also lower than for B14-65666 ($>10^9 L_\odot$). We, therefore, conclude that shock excitation is less dominant in [C II] emission in B14-65666 unless the shock mechanism significantly differs between the two objects.

### 5.3. Nitrogen-to-oxygen Abundance Ratio

As seen in dwarf galaxies (e.g., Lequeux et al. 1979; Vila-Costas & Edmunds 1993) and SDSS galaxies (Andrews & Martini 2013), the N/O abundance ratio is almost constant as $\log_{10} (N/O) \simeq 1.5$ at low metallicity, and it drastically increases when the metallicity exceeds a certain value. A simple explanation of this N/O trend is a combination of the primary and secondary nucleosynthetic nitrogen; the primary production of nitrogen is independent of the initial metallicities in stars, whereas the secondary production that occurred in the CNO cycle is proportional to the initial carbon or oxygen abundance (Pagel 2009).

The N/O ratio affects the intensity ratios between nitrogen and oxygen atoms/ions emission lines. In some photoionization models, the N/O ratio is assumed as a function of metallicity (Nagao et al. 2011; Pereira-Santaella et al. 2017; Rigopoulou et al. 2018), but it is possible that this relation changes at high redshift. Given the nebular parameters and input spectrum (i.e., a certain fixed ionization structure), photoionization models can predict abundance ratios from observed emission-line intensity ratios. In FIR bands, the [N III] 57 $\mu$m/[O III] 52 $\mu$m line ratio is used for N/O measurements (e.g., Lester et al. 1983; Rubin et al. 1988; Peng et al. 2021), as both lines have similar ionization potentials and critical densities. For B14-65666, the [N III] 57 $\mu$m and [O III] 52 $\mu$m lines are accessible in ALMA Band 9, however, they still require expensive observations. Instead, by assuming the
The nitrogen-to-oxygen abundance ratio as a function of the metallicity. Left: Cloudy model grid as a function of metallicity and ionization parameter, in the case of log $n_H = 2.0$ and log $L_{N_{\text{II}}}/L_{O_{\text{I}}} \lesssim -1.63$, which is the observed $3\sigma$ upper limit of a luminosity ratio. The symbol colors and sizes depend on the ionization parameter. The black solid lines show the average relations of extragalactic HII regions (Pilyugin et al. 2012) and local SDSS galaxies (Andrews & Martini 2013) estimated using the direct temperature method. The gray dashed lines indicate the solar values. Right: The red circles show the case of B14-65666 at $C_{\text{PDR}} = 1.0$ as a function of metallicity, obtained from the measured luminosity ratio, log $L_{N_{\text{II}}}/L_{O_{\text{I}}} \lesssim -1.63$. The range of the metallicity inferred from the SED fitting by Hashimoto et al. (2019) is $12 + \log(O/H) = 7.97$–8.57, corresponding to $Z = 0.2$–0.8 $Z_\odot$ (red dotted line). The small orange circles show the case of $C_{\text{PDR}} = 0.1$. The orange upside-down triangles show the case in which the ionization parameter is fixed at $U = -2.7$. The blue and cyan data points show the $z \sim 2$ galaxies without error bars: Strom et al. (2018, blue crosses), Steidel et al. (2016, blue square), and Kojima et al. (2017, cyan pentagon). The N/O ratio is constrained to be subsolar if the metallicity of B14-65666 is 12 + $\log(O/H) > 8.4$.

nebular parameters derived from the [O III] and [C II] emission lines (Section 5.2), we constrain the N/O abundance ratio at $z \sim 7$ from our upper limits of the luminosity ratio between [N II] 122 $\mu$m and [O III] 88 $\mu$m ($L_{N_{\text{II}}}/L_{O_{\text{I}}} \lesssim 88$). We convert $L_{N_{\text{II}}}/L_{O_{\text{I}}} \lesssim 88$ to N/O with Cloudy models and the nebular parameters obtained in Section 5.2, which are functions of metallicity (see Figure 8). The observed line-luminosity ratio is $L_{N_{\text{II}}}/L_{O_{\text{I}}} < -1.63$. For each nebular parameter set, we prepare models with $\log(O/N)$ ranging from $-2$ to $0$ in steps of $0.5$. We note that $n_H$ is included in our calculations even though $L_{N_{\text{II}}}/L_{O_{\text{I}}} < -1.63$ is almost independent of $n_H$ due to similar critical densities between [N II] 122 $\mu$m and [O III] 88 $\mu$m. We compare the observed $L_{N_{\text{II}}}/L_{O_{\text{I}}} < -1.63$ ratios and the Cloudy models to obtain the upper limits of N/O as a function of $U$ and $Z$. The left panel of Figure 9 shows a Cloudy model grid in the case of $L_{N_{\text{II}}}/L_{O_{\text{I}}} < 2.0$ and $L_{N_{\text{II}}}/L_{O_{\text{I}}} < -1.63$. At a fixed $Z$, a higher $U$ results in a higher N/O upper limit (i.e., a weaker N/O constraint). Because the low SFR yields high-U solutions among the three SFR cases considered in Section 5.2, the estimated N/O upper limits become the highest (weakest) at the low SFR. To simply express N/O as a function of $Z$, we take the highest N/O ratios as an upper limit at each in the following.

The right panel of Figure 9 illustrates the upper limits of the N/O abundance ratio for B14-65666 as a function of metallicity. Given that the solar value of $12 + \log(O/H) = 8.69$ (Asplund et al. 2009), the metallicity $Z$ is converted to the O/H abundance ratio. The N/O value is well constrained at a high metallicity regime. This originates from a model prediction of relatively high $L_{N_{\text{II}}}/L_{O_{\text{I}}} < 84$ for the range of ionization parameters at high metallicities. At $12 + \log(O/H) > 8.4$, $\log_e(N/O)$ is less than the solar value of $-0.84$ (Asplund et al. 2009). At a higher metallicity of $12 + \log(O/H) > 8.5$, the $\log_e(N/O)$ upper limits become less than the average relation of extragalactic HII regions (Pilyugin et al. 2012). This is consistent with an implication of the Rigopoulou et al. (2018) model that the metallicity of B14-65666 is $\lesssim 0.6 Z_\odot$ if $\log_e(U) \approx -2.7$ and the N/O ratio follows a local N/O–Z relation (Section 5.2). On the other hand, the N/O constraint is very weak at $12 + \log(O/H) < 8.3$ due to high ionization parameters of log $U \gtrsim -2.5$. If the metallicity of B14-65666 is $12 + \log(O/H) < 8.3$, our observations cannot produce a meaningful constraint on the N/O abundance, implying that we need more sensitive observations by one to two orders of magnitude to detect the [N II] 122 $\mu$m emission line from the $z \sim 7$ galaxy. The small orange circles in Figure 9 depict the case of $C_{\text{PDR}} = 0.1$. We find that the low PDR covering fraction only weakly affects the upper limits of the N/O ratio by 0.3 dex at most. As shown in Figure 8, the low $C_{\text{PDR}}$ slightly changes $U$ in the low-SFR case, which influences the N/O upper limit. Although $n_H$ decreases in this case, $L_{N_{\text{II}}}/L_{O_{\text{I}}} \lesssim 88$ is almost independent of $n_H$ and the N/O constraints are not affected. Therefore, the lower $C_{\text{PDR}}$ does not change the N/O abundance very much.

The weak N/O upper limits at $12 + \log(O/H) < 8.3$ originate from the high ionization parameters of log $U \gtrsim -2.5$. If the ionization parameter of B14-65666 is similar to those of local and $z \sim 2$ galaxies, the upper limits would become more stringent. We test whether this case is possible for our galaxy by fixing $\log_e(U) = -2.7$ and by changing $C_{\text{PDR}}$ from 0.05 to 1.0 on the $L_{O_{\text{I}}} < 1.63$ diagram. In this analysis we choose nebular parameter sets that can model the observed value within the SFR uncertainty of 162 $M_\odot$ yr$^{-1}$ and take the highest N/O in the parameter sets as the upper limits at fixed metallicities. The results are depicted with the orange upside-down triangles in Figure 8. The assumption of log $U = -2.7$ gives similar upper limits to the $C_{\text{PDR}} = 1.0$
case (red circles) at $12 + \log_{10}(O/H) > 8.3$, while the upper limit is constant at $\log_{10}(N/O) = -0.87$ at lower metallicities of $12 + \log_{10}(O/H) < 8.3$, as predicted from the left panel of Figure 9. This N/O upper limit is three times lower than those shown by the red and orange circles for which log $U$ increases as the metallicity decreases. If $\log_{10} U = -2.7$, the N/O ratio of this galaxy is restricted to be subsolar, irrespective of its intrinsic metallicity. Our model requires a low PDR covering fraction ($C_{\text{PDR}} < 1$) and high SFR (282 $M_{\odot}\text{yr}^{-1}$) to keep $\log_{10} U = -2.7$ at lower metallicities. We cannot plot the data point at $12 + \log_{10}(O/H) = 8.0$ in the figure because there are no models with $\log_{10} U = -2.7$ at this metallicity within the SFR uncertainty interval.

Our N/O upper limit is roughly consistent with $z \sim 2$ studies. Steidel et al. (2016) stacked the KBSS-MOSFIRE spectra to compute their typical N/O, and Strom et al. (2018) estimated N/O for individual KBSS-MOSFIRE galaxies with photoionization models. These N/O ratios are comparable to those of the local extragalactic H II regions presented by Pilyugin et al. (2012). The relatively low-metallicity galaxies at $z \sim 2$ studied by Kojima et al. (2017) exhibit higher $\log_{10}(N/O)$ than local galaxies at fixed metallicities, which are measured using a direct temperature method. Most of these N/O ratios at $z \sim 2$ are lower than the upper limit of B14-65666. Our upper limits are also consistent with the nearby analogs of LBGs in Loaiza-Agudelo et al. (2020).

### 5.4. Predicted BPT Diagram

As noted in the previous section, the photoionization model can convert an emission-line flux into another line flux for the same ion. This enables us to predict the position of B14-65666 on the BPT diagram from our FIR line fluxes. We estimate optical-line ratios of [O III]Å5007/Hβ and [N II]Å6583/Hβ from the FIR [O III] 88 μm and [N II] 122 μm line fluxes, respectively, using the Cloudy models with the nebular parameters obtained in Section 5.2. In this model, [N II]Å6583/Hβ is given as an upper limit because the [N II] 122 μm flux is constrained as the 3σ upper limit in our observations. The Hα/Hβ line ratio is also computed from the model. In this way, we obtain the modeled [O III]Å5007/Hβ and [N II]Å6583/Hα line ratios for B14-65666.

Figure 10 shows a BPT diagram. In general, dust attenuation is negligible on the BPT diagram because the diagram takes the ratios of the emission lines with close wavelengths. The [O III] 88 μm and [N II] 122 μm line fluxes are not affected by dust attenuation because of their long wavelengths. For these reasons, our estimations can be compared with values in the literature without concerns about dust attenuation.

The estimated optical-line ratios for B14-65666 are $\log_{10}(\text{[O III]}/\text{H}/\beta) = 0.55 \pm 0.02$ and $\log_{10}(\text{[N II]}/\text{H}/\alpha) < -0.71$ at $Z = 0.4 Z_{\odot}$. The [O III] H/β ratios become high at $Z = 0.2 Z_{\odot}$, and lower at $Z = 0.8 Z_{\odot}$, while both [N II]/H/α upper limits become lower than the value at $Z = 0.4 Z_{\odot}$. These values are depicted with the red circles in Figure 10. We note that B14-65666 is located in the region where star-forming galaxies are distributed on the BPT diagram (Kauffmann et al. 2003), which is a natural consequence of including the starbursting spectrum into the Cloudy model calculations (Section 5.2). We are assuming that the entire emission-line fluxes originate from star formation, not from AGNs. When $C_{\text{PDR}} = 0.1$, the data points shown by the small orange circles move to the lower left, reflecting the low ionization parameter and hydrogen density.

![Figure 10. Estimated location of the B14-65666 upper limits on the BPT diagram. The location is computed from the photoionization model with the nebular parameters $U$, $n_{e}$, and $Z$ (see the text in Section 5.4). The red circles are assumed to be $C_{\text{PDR}} = 1.0$ and $Z = 0.2, 0.4, 0.8 Z_{\odot}$, where low-metallicity data points show high [O III]/Hβ. The orange small circles denote the locations in the case of $C_{\text{PDR}} = 0.1$. The black density map indicates local SDSS galaxies. The blue crosses and cyan triangles indicate star-forming galaxies at $z \sim 2$ from the KBSS-MOSFIRE survey (Strom et al. 2017) and the MOSDEF survey (Shivaei et al. 2018), respectively. The black and blue lines represent the best-fit relations for the $z \sim 0$ SDSS galaxies and the $z \sim 2$ KBSS-MOSFIRE galaxies, respectively (Strom et al. 2017). As seen, B14-65666 is expected to be located on or below the $z \sim 2$ relation.](https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/)

To compare our results with low-redshift galaxies, we plot the distributions of local SDSS and $z \sim 2$ star-forming galaxies in Figure 10. The flux ratios of SDSS galaxies are taken from the MPA/JHU catalog. The $z \sim 2$ galaxies are taken from the KBSS-MOSFIRE survey (Strom et al. 2017) and the MOSDEF survey (Shivaei et al. 2018). Our upper limits shown with the red circles ($C_{\text{PDR}} = 1.0$) are located above the local average relation and around the $z \sim 2$ relation (Strom et al. 2017). It is quite possible that B14-65666 is located below the average relation of the $z \sim 2$ galaxies even though our model provides only upper limits, considering the weak [N II] 122 μm flux suggested from the N/O upper limits at $Z < 0.4 Z_{\odot}$ (Figure 9). In the case of $C_{\text{PDR}} = 0.1$ (small orange circles), the upper limits are located around the $z \sim 0$ galaxies. At $Z = 0.8 Z_{\odot}$, in this case, the especially low [N II]/Hα and [O III]/H/β values are predicted because the [N II] 122 μm line was undetected despite the low metallicity and low ionization parameters. In summary, our model predicts that B14-65666, at $z \sim 7$, is located on or below the average relation at $z \sim 2$ on the BPT diagram. If $C_{\text{PDR}}$ is low, the location will become close to the $z \sim 0$ relation.

If B14-65666 is representative of the entire galaxy population at $z \sim 7$, we can discuss the redshift evolution from $z \sim 7$ to 2 on the BPT diagram by comparing the location of B14-65666 with the $z \sim 2$ relation. However, the large dispersions of the galaxy distributions on the BPT diagram at $z \sim 0$ and 2 raise the possibility that B14-65666 is not the average relation at $z \sim 7$. In addition, the high UV luminosity and merger geometry of B14-65666 may not support the assumption that this galaxy is
representative of typical galaxies at $z \sim 7$. Further ALMA observations will explore the average ionization properties and distribution on the BPT diagram of the high-redshift galaxies. More directly, the upcoming JWST will provide us with opportunities to plot the BPT diagram at high redshift by observing B14-65666 and other high-redshift galaxies in near- to mid-infrared bands.

6. Summary

We have performed ALMA Band 7 observations of an LBG at $z = 7.15$, B14-65666, to target the [N II] 122 $\mu$m FIR fine-structure line and underlying dust continuum emission. B14-65666 is the first object detected in [O III] 88 $\mu$m, [C II] 158 $\mu$m, and dust continuum emission at such high redshift (“Big Three Dragons”; Hashimoto et al. 2019).

The dust continuum at 120 $\mu$m is detected with S/N = 18.9. We combine the dust continuum flux at 120 $\mu$m with the previous measurements at 90 $\mu$m and 160 $\mu$m to perform two types of FIR SED fitting. The modified blackbody fitting results in a dust temperature $T_d = 80$ to 40 K and a dust mass $M_d \sim 10^{6.6}$ to $10^{7.5} M_\odot$ with an emissivity index $\beta = 1$ to 2. The corresponding IR luminosity spans $\log L_{120}/L_\odot = 12.0$ to 11.6. The results of the radiative equilibrium fitting, proposed by Inoue et al. (2020), are found to be similar to the results for another $z \sim 7$ dusty star-forming galaxy, A1689zD1. Simple assumptions of the shell and homogeneous geometries appear to be invalid because the geometries prefer too high IR luminosity. The clumpy geometry leads to the same best-fit results as the modified blackbody, with a best-fit clumpiness parameter of $\xi_{cl} = 0.1$–0.4.

The [N II] 122 $\mu$m emission line is not detected. The 3$\sigma$ upper limit of [N II] luminosity is $8.1 \times 10^7 L_\odot$. We constrain the nebular parameters of B14-65666 as functions of metallicity with a photoionization code Cloudy by modeling the [N II] 122 $\mu$m upper limits, along with the [O III] 88 $\mu$m and [C II] 158 $\mu$m line fluxes and the SED SFR. If the metallicity of B14-65666 is high ($Z > 0.4 Z_\odot$), the ionization parameters and hydrogen densities are $\log_{10} U \sim -2.7 \pm 0.1$ and $n_H \sim 50$–250 cm$^{-3}$, respectively. The two nebular parameter values are consistent with those measured in low-redshift galaxies. If $Z \sim 0.4 Z_\odot$, the $U$ and $n$ drastically increase and decrease, respectively, with a decrease in metallicity. This is due to the high $L_{\text{O III}}/L_{\text{H}\alpha}$ ratio, that is, the observed high $L_{\text{O III}}/L_{\text{H}\alpha}$ ratio of this galaxy. In the case of a low PDR covering fraction ($C_{\text{PDR}} = 0.1$), lower $U$ and $n_H$ are expected, while the results are qualitatively the same.

The constraints on the nitrogen-to-oxygen abundance ratio, N/O, also largely depend on the assumed metallicity. The obtained upper limit of the N/O ratio monotonically decreases as the assumed metallicity increases. At $12 + \log_{10} (O/H) \gtrsim 8.4$, the N/O ratios should be subsolar and upper limits are comparable to the N/O ratio of local and $z \sim 2$ galaxies. In contrast, our observations cannot provide a meaningful constraint at $12 + \log_{10} (O/H) < 8.3$. The N/O ratio is insignificantly affected by the differences of the PDR covering fractions between $C_{\text{PDR}} = 0.1$ and 1.0. If we fix the ionization parameter at $\log U = -2.7$ in our model, the N/O ratios are restricted to be subsolar even at $12 + \log_{10} (O/H) < 8.3$ with a small PDR covering fraction and a high SFR.

The Cloudy models also predict the location of the galaxy at $z \sim 7$ on the BPT diagram, using the nebular parameters estimated from the FIR lines. The upper limits of B14-65666 are predicted to be located in the distribution of star-forming galaxies at $z \sim 2$. The location of B14-65666 may be below the $z \sim 2$ average relation given the weak N/O upper limits. In the case of $C_{\text{PDR}} = 0.1$, the upper limits are located around the distribution of local galaxies. Further ALMA statistical observations and rest-frame optical-line observations with JWST will provide opportunities for addressing the high-redshift BPT diagram.

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Software: CASA (McMullin et al. 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), IPython (Perez & Granger 2007), Matplotlib (Hunter 2007), Astropy (Astropy Collaboration et al. 2013, 2018), APpy (Robitaille & Bressert 2012), CLOUDY (Ferland et al. 2017), PyNeb (Luridiana et al. 2015).
Appendix

Results of the Radiative Equilibrium Fitting Depending on $\beta$ 

FIR SED fitting depends on the assumed emissivity index $\beta$. The results for $\beta = 2.0$ are shown in the main text. Figure 11 shows the fitting results of the radiative equilibrium algorithm, and Figure 12 shows the best-fit FIR SEDs in the case of $\beta = 1.0$ and 1.5. Figure 13 shows the distribution of the solutions in the clumpy geometry for $\beta = 1.0$ and 1.5. Table A1 summarizes the results of the FIR SED fitting, including the modified blackbody fitting.

Figure 11. Same as Figure 4 but for the emissivity indices $\beta = 1.0$ and 1.5.

Figure 12. Same as Figure 4 but for the emissivity indices $\beta = 1.0$ and 1.5.

Figure 13. Same as Figure 4 but for the emissivity indices $\beta = 1.0$ and 1.5. In these cases, the crosses are the highest peaks, and the plus signs are the second-highest peaks.
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Table A1
A Summary of the FIR SED Fitting Results

| Cases                        | $\chi^2$ | d.o.f. | $T_A$ (K) | $\log_{10}(M_\star/M_\odot)$ | $\log_{10}(L_{IR}/L_{\odot})$ | SFR$_{IR}$ ($M_\odot$ yr$^{-1}$) |
|------------------------------|----------|--------|-----------|-------------------------------|---------------------------------|---------------------------------|
| Modified blackbody fitting   |          |        |           |                               |                                 |                                 |
| $\beta = 2.0$                | 1.45     | 1      | 40.8      | 7.45 (6.96–8.06)              | ...                             | 11.62 (11.35–12.19)             | 72                              |
| $\beta = 1.5$                | 1.07     | 1      | 53.7      | 7.06 (6.52–7.57)              | ...                             | 11.80 (11.39–12.64)             | 110                             |
| $\beta = 1.0$                | 0.74     | 1      | 78.7      | 6.64 (5.86–7.15)              | ...                             | 12.09 (11.50–13.86)             | 210                             |
| Radiative equilibrium fitting, shell model |          |        |           |                               |                                 |                                 |
| $\beta = 2.0$                | 4.53     | 2      | 96.6      | 6.55 (6.33–6.71)              | ...                             | 12.97 (12.62–13.55)             | 1600                            |
| $\beta = 1.5$                | 2.19     | 2      | 100.8     | 6.49 (6.27–6.64)              | ...                             | 12.72 (12.41–13.25)             | 900                             |
| $\beta = 1.0$                | 0.88     | 2      | 105.6     | 6.41 (6.20–6.56)              | ...                             | 12.49 (12.21–12.95)             | 530                             |
| Radiative equilibrium fitting, homogeneous model |          |        |           |                               |                                 |                                 |
| $\beta = 2.0$                | 3.62     | 2      | 79.7      | 6.71 (6.59–6.81)              | ...                             | 12.63 (12.44–12.87)             | 730                             |
| $\beta = 1.5$                | 1.85     | 2      | 87.5      | 6.59 (6.47–6.69)              | ...                             | 12.50 (12.32–12.75)             | 540                             |
| $\beta = 1.0$                | 0.82     | 2      | 96.8      | 6.47 (6.34–6.58)              | ...                             | 12.37 (12.19–12.62)             | 400                             |
| Radiative equilibrium fitting, clumpy model |          |        |           |                               |                                 |                                 |
| $\beta = 2.0$                | 1.45     | 1      | 40.7      | 7.45 (6.91–8.21)              | −0.43 (−1.09–−0.11)            | 11.62 (11.42–12.45)             | 72                              |
| $\beta = 1.5$                | 1.07     | 1      | 53.5      | 7.06 (6.64–7.65)              | −0.59 (−0.19)                  | 11.79 (11.40–12.43)             | 110                             |
| $\beta = 1.0$                | 0.74     | 1      | 79.0      | 6.63 (6.44–7.20)              | −0.93 (−0.31)                  | 12.09 (11.48–12.42)             | 210                             |

Note. The values in the parentheses indicate the 68% ranges around the best-fit values. For the modified blackbody fitting, both dust temperature, $T_A$, and dust mass, $M_\star$, are the fitting parameters. For the radiative equilibrium fitting, $T_A$ and $M_\star$ are connected, and only one of them is the actual fitting parameter. In the clumpy model, another fitting parameter—the clumpiness, $\xi_c$—is introduced. The IR luminosity, $L_{IR}$, is a derived quantity obtained from the integral of the modified blackbody function over the entire frequency range. The IR star formation rate, SFR$_{IR}$, is derived from $L_{IR}$ with the conversion of Kennicutt (1998).

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