CNO Emission of an Unlensed Submillimeter Galaxy at $z = 4.3$

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Abstract

We present the results from Atacama Large Millimeter/submillimeter Array observations of [N II] 205 μm, [C II] 158 μm, and [O III] 88 μm lines in an unlensed submillimeter galaxy at $z = 4.3$, COSMOS-AzTEC-1, hosting a compact starburst core with an effective radius of ~1 kpc. The [C II] and [N II] emission are spatially resolved in 0″3-resolution (1 kpc in radius). The kinematic properties of the [N II] emission are consistent with those of the CO(4–3) and [C II] emission, suggesting that the ionized gas feels the same gravitational potential as the associated molecular gas and photodissociation regions (PDRs). On the other hand, the spatial extent is different among the lines and dust continuum: the [C II] emitting gas is the most extended and the dust is the most compact, leading to a difference of the physical conditions in the interstellar medium. We derive the incident far-ultraviolet flux and the hydrogen gas density through PDR modeling by properly subtracting the contribution of ionized gas to the total [C II] emission. The observed [C II] emission is likely produced by dense PDRs with $n_{\text{H}^0} = 10^{5.5–5.75}$ cm$^{-3}$ and $G_0 = 10^{15.5–15.75}$ in the central 1 kpc region and $n_{\text{H}^0} = 10^{5.0–5.25}$ cm$^{-3}$ and $G_0 = 10^{12.25–13.25}$ in the central 3 kpc region. We have also successfully measured the line ratio of [O III]/[N II] in the central 3 kpc region of COSMOS-AzTEC-1 at $z = 4.3$, which is the highest redshift where both nitrogen and oxygen lines are detected. Under the most likely physical conditions, the measured luminosity ratio of $L_{\text{CO}}/L_{\text{[N II]}} = 6.4 \pm 2.2$ indicates a near solar metallicity with $Z_{\text{gas}} = 0.7–1.0 Z_{\odot}$, suggesting a chemically evolved system at $z = 4.3$.

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

1. Introduction

Submillimeter bright galaxies (SMGs) at $z > 3$ are the most likely progenitors of elliptical galaxies in the present-day universe. They are intensively forming stars in the central 1 kpc region (e.g., Hodge et al. 2015; Ikarashi et al. 2015) and are massive with a stellar mass of $M_\star > 10^{11} M_\odot$ (Michałowski et al. 2014). The size is comparable to massive, compact quiescent galaxies at $z \sim 2$, which could eventually evolve into larger ellipticals by dry mergers (e.g., van Dokkum et al. 2015). These results suggest an evolutionary link from SMGs at $z > 3$ to ellipticals at $z = 0$.

The far-infrared (FIR) fine structure lines of C, N, and O offer valuable insights into the physical conditions in the interstellar medium (ISM) of SMGs at $z > 3$. The [C II] 158 μm line, primarily emitted from photodissociation regions (PDRs), is typically the brightest among the FIR fine structure lines (e.g., Díaz-Santos et al. 2017; Herrera-Camus et al. 2018). Observations of [C II], CO line, and FIR continuum emission successfully characterize the physical properties (gas density and strength of radiation field) through theoretical models taking into account the chemistry, radiative transfer, and thermal balance of the neutral ISM (e.g., Hollenbach & Tielens 1999; Kaufman et al. 1999). The [N II] 205 μm line (or [N II] 122 μm) and the [O III] 88 μm line (or [O III] 52 μm) emission arise only from ionized gas as the ionization potential is higher than that of hydrogen (>13.6 eV). In SMGs at $z > 3$, these lines have been detected with ground-based telescopes (e.g., Ferkinhoff et al. 2010; Pavesi et al. 2016, 2018; Lu et al. 2017; Marrone et al. 2018; Vishwakarma et al. 2018; Walter et al. 2018) and with Herschel (e.g., Valchovanov et al. 2011; Zhang et al. 2018). The line ratio of nitrogen and oxygen can be used as an indicator of gas-phase metallicity, which is commonly estimated from observations of rest-frame optical lines (Pereira-Santaella et al. 2017; Rigoupolou et al. 2018). The metallicity is one of the most important parameters to investigate galaxy formation because it imprints the past star formation histories. For highly dust-obsured sources such as SMGs, the FIR lines have a big advantage over the optical lines in that they are less affected by dust extinction.

In this paper, we report results from Atacama Large Millimeter/submillimeter Array (ALMA) observations of an extreme starburst galaxy at $z = 4.342$, COSMOS-AzTEC-1 hereafter, to study the spatial extent of the FIR fine structure lines and the physical conditions of gas in the PDRs and the ionized regions. COSMOS-AzTEC-1 is one of the brightest SMGs, but not magnified by gravitational lensing (Younger et al. 2007; Scott et al. 2008; Yun et al. 2015; Iono et al. 2016). The high-resolution ALMA observations enable us to spatially
resolve the FIR fine structure lines and investigate the kinematic structures without uncertainties in lens modeling.

2. Observations and Results

Following our previous observations of the CO(4–3) emission line with ALMA Band-3 receivers (Tadaki et al. 2018), we have made new observations of the [N II] 205 μm, [C II] 158 μm, and [O III] 88 μm lines with Band-6, -7, and -9, respectively. The observation date, the baseline length, the frequency coverage, and the integration time are summarized in Table 1. The data were calibrated in the standard manner using CASA (McMullin et al. 2007). We create two cubes with different resolutions (0′′3 and 0′′9), corresponding to 1 kpc and 3 kpc in radius, by applying a ν tapering and Gaussian smoothing (Table 1). We cleaned the cubes with a channel width of 50 km s$^{-1}$ down to the 1σ level in a circular mask with a diameter of 1′5. The resultant noise levels are listed in Table 1. We also make a 0′′3-resolution map of the dust emission by 0′′2 and the position angle to the underlying component since interferometric maps could create artificial clumps on an extended disk (Hodge et al. 2016; Gullberg et al. 2018). Therefore, we give the 3σ upper limit in the 0′′3-resolution [O III] flux map and measure the peak fluxes in other maps (S$^{peak,0′′3}_{dv}$ in Table 1).

3. Analysis

3.1. Gas Kinematics

For the CO(4–3), [N II], [C II] emission, the velocity field maps all show a monotonic gradient along a similar kinematic major axis, suggesting rotation of the gas (Figure 1). We fit the 0′′3-resolution cubes with dynamical models of a thick exponential disk using the GalPaK3D v1.9.1 code (Bouché et al. 2015) to determine the maximum circular velocity $V_{max}$, local velocity dispersion $\sigma_0$, half-light radius $R_{1/2,\text{image}}$, inclination, and position angle. We assume an arctan rotation curve and a constant $\sigma_0$ within a galaxy in the models. From the modeling of the [C II] cube with the highest signal-to-noise ratios, we derive that the inclination is 41°8 ± 0′′2 and the position angle is −65°7 ± 0′′2. The fitting errors are typically 2%–3%, based on the 95th percentile of the last 60% of the Markov chain Monte Carlo for 20,000 iterations. However, the comparison between data cubes with different clean parameters, leading to a different spatial resolution, shows systematic errors of ~10% in all parameters (K. Tadaki et al. 2019, in preparation). For fair comparisons of $V_{max}$ and local velocity dispersion $\sigma_0$ among the lines, we fix the inclination and the position angle to the [C II] values for modeling of the CO and [N II] cubes. Table 1 summarizes the best-fit values taking into account the systematic errors of 10%. The three lines have the similar

| Observations and Imaging Parameters | ALMA Band-3 CO (4–3) | ALMA Band-6 [N II] 205 μm | ALMA Band-7 [C II] 158 μm | ALMA Band-9 [O III] 88 μm |
|------------------------------------|----------------------|--------------------------|-------------------------|-------------------------|
| observation date                   | 2017/10.11           | 2018/11                  | 2017/12                 | 2018/11/12              |
| baseline length                    | 12–4664              | 14–1277                  | 18–2967                 | 32–2017                 |
| frequency coverage                 | 85.4–89.1 GHz        | 256.0–259.8 GHz          | 342.8–346.7 GHz         | 630.5–638.0 GHz         |
| on-source time                     | 97.5–101.2 minutes   | 270.9–274.7 minutes      | 354.9–258.7 minutes     | 100                     |
| ν tapering for 0′′3-resolution maps| 0′′2                 | n/a                      | 0′′2                    | 0′′1                    |
| ν tapering for 0′′9-resolution maps| 0′′6                 | 0′′4                    | 0′′5                    | 0′′5                    |
| $\sigma_{50,\text{km,s}^{-1},3}$   | 0.10                 | 0.09                     | 0.41                    | 1.5                     |
| $\sigma_{50,\text{km,s}^{-1},9}$   | 0.25                 | 0.17                     | 0.89                    | 3.0                     |

| Fluxes and Luminosities            |                     |                          |                         |
|------------------------------------|----------------------|--------------------------|-------------------------|
| $S^{peak,0′′3}_{dv}$               | (Jy beam$^{-1}$ km$^{-1}$ s$^{-1}$) | 0.53 ± 0.02              | 0.35 ± 0.02              | 4.23 ± 0.08             | <0.88                   |
| $S^{peak,0′′9}_{dv}$               | (Jy beam$^{-1}$ km$^{-1}$ s$^{-1}$) | 0.99 ± 0.04              | 0.78 ± 0.03              | 10.94 ± 0.21            | 2.15 ± 0.54             |
| $L^{peak,0′′3}$                    | (10$^8$ $L_{\odot}$) | 0.75 ± 0.05              | 1.58 ± 0.17              | 24.4 ± 2.5              | <9.0                    |
| $L^{peak,0′′9}$                    | (10$^8$ $L_{\odot}$) | 1.39 ± 0.09              | 3.46 ± 0.37              | 63.2 ± 6.4              | 22.1 ± 7.1              |

| Kinematic Properties              |                     |                          |                         |
|------------------------------------|----------------------|--------------------------|-------------------------|
| $V_{max}$                          | (km s$^{-1}$)        | 233 ± 24                 | 234 ± 24                | 217 ± 22                |
| $\sigma_0$                         | (km s$^{-1}$)        | 94 ± 9                   | 94 ± 10                 | 77 ± 8                  |
| $R_{1/2,\text{image}}$             | (kpc)                | 1.24 ± 0.12              | 1.47 ± 0.15             | 1.71 ± 0.17             |
| $R_{1/2,\text{visibility}}$        | (kpc)                | 1.24 ± 0.13              | 1.53 ± 0.18             | 2.01 ± 0.08             |

Table 1
Summary of Observations and Line Properties in AzTEC-1
although they trace a different gas phase. The agreement implies that the ionized gas feels the same gravitational potential as the associated PDR and molecular gas (Übler et al. 2018). The velocity dispersion of [C II] emission, while its value is slightly smaller than that of CO and [N II] emission, is in agreement with the other velocity dispersions given the level of precision in the measurements. We confirm that COSMOS-AzTEC-1 is surely rotation-dominated with \( V_{\text{max}} / \sigma_0 = 2.5 - 2.8 \).

The disk modeling above gives different \( R_{1/2} \) among the lines as contrasted with the similar kinematic properties. To verify this result, we fit the visibility data to exponential disk models using the UVMULTIFIT code (Martí-Vidal et al. 2014). The visibility-based analysis does not depend on clean parameters for reconstructing the images and is less affected by the spatial resolution. The half-light radii are similar between the two methods (Table 1). We also derive that the half-light radius of the rest-frame 89 \( \mu m \) continuum emission is \( R_{1/2, \text{visibility}} = 0.81 \pm 0.04 \) kpc. The difference of the spatial extent is clearly seen in the radial profile of the surface brightness along the kinematic major axis (Figure 2). The CO radial profile is similar to the [N II] one although they have slightly different \( R_{1/2} \). The most conspicuous result is that the [C II] emission is the most extended and the dust continuum is the most compact. As the rest-frame 89 \( \mu m \) is generally close to the peak wavelength of dust emission heated by star formation, the continuum emission directly traces the FIR luminosities and thus dust-obscured star formation rates. This significant difference between [C II] and FIR would lead to a radial variation in the strength of radiation field, which is seen in both nearby (e.g., Díaz-Santos et al. 2017; Kapala et al. 2017) and high-redshift galaxies (Lamarche et al. 2018).

3.2. Far-infrared Luminosities

ALMA multiband observations provide multidata point of continuum emission, constraining a spectral energy distribution (SED) of dust component. We create \( 0''3 \) - and \( 0''9 \)-resolution continuum maps in each spectral window for the Band-3, -6, -7, and -9 data and also use \( 0''9 \)-resolution Band-4 data (2 mm; Tadaki et al. 2018). The flux uncertainties are mainly dominated by the flux calibration errors (5% at Band-3 and -4, 10% at Band-6 and -7, 20% at Band-9; ALMA Technical Handbook) rather than the signal-to-noise ratios of the detections. The measured continuum fluxes are given in Table 2. To estimate the FIR luminosities \( L_{\text{FIR}} \) in the rest-frame wavelength range of 42.5–122.5 \( \mu m \), we model the observed SEDs at 10 bands in the central 1 kpc region (\( V_{\text{max}} \))
resolution map) and at 12-bands in the central 3 kpc region (0''9-resolution map) using the CIGALE code (Burgarella et al. 2005; Boquien et al. 2019). We adopt a simple analytic model with a single modified blackbody radiation, characterized by dust temperature $T_{\text{dust}}$ and an emissivity index $\beta$, and a power-law emission (Casey 2012). The power-law component has little contribution to our modeling since short wavelength data is not included ($\lambda < 80 \mu$m in the rest-frame). Figure 3 shows the observed SEDs and the best-fit models giving $L_{\text{FIR}} = (5.3 \pm 1.1) \times 10^{12} L_\odot$, $T_{\text{dust}} = 59^{+2}_{-3} K$ and $\beta = 2.1^{+0.2}_{-0.1}$ in the central 1 kpc region and $L_{\text{FIR}} = (7.9 \pm 1.7) \times 10^{12} L_\odot$, $T_{\text{dust}} = 54^{+4}_{-3} K$, and $\beta = 2.4^{+0.1}_{-0.2}$ in the central 3 kpc region. The central 1 kpc region has a slightly higher dust temperature than the outer regions but the difference is within the fitting errors.

3.3. Gas Properties in PDR

The [C II] emission is more extended than the CO(4–3) and the rest-frame 89 \mu m continuum emission (Section 3.1). This does not necessarily mean different beam filling factors among the three emission because the kiloparsec-scale resolution is much larger than individual PDRs. Given that we observe the cumulative emission from many PDRs, the difference in the spatial distributions would reflect a radial variation in the typical gas properties. We calculate the luminosities of CO and [C II] emission both in the central 1 kpc region and the central 3 kpc region, with taking into account the systematic errors on the flux calibration as well as the random errors based on the signal-to-noise ratio ($L_{\text{peak}}$ in Table 1). By comparing our measurements with values predicted by theoretical models of Kaufman et al. 1999, we determine the hydrogen gas density $n_{H_{\text{PDR}}}$ and the strength of the incident far-ultraviolet (FUV) radiation fields with $6 < h\nu < 13.6$ eV, $G_0$.

Standard models of Kaufman et al. (1999) consider a simple geometry of one-dimensional plane-parallel slabs illuminated from one side by an FUV flux $G_0$. [C II] line and dust continuum emission are generally optically thin while CO emission is optically thick. Therefore, we increase the observed CO luminosities by a factor of two to count the emission from the far side. As [C II] emission comes from ionized regions as well as PDRs, we need to subtract the contribution of ionized gas from observed [C II] luminosities. A [N II] 205 \mu m line is useful for estimating [C II] luminosities arising from ionized regions [C II] ion since its critical density and excitation energy are similar to those of a [C II] line. Here, we assume a line ratio of [C II] ion/[N II] = 2, predicted from photoionization models, in the ionized gas (Section 3.4). The fraction of [C II] originating from PDRs is [C II] PDR/[C II] = 81% in the central 1 kpc region and [C II] PDR/[C II] = 84% in the central 1 kpc region and [C II] PDR/[C II] = 84% in the central 1 kpc region.
3 kpc region, which are similar to the typical values in local luminous and ultra-luminous infrared galaxies (LIRGs and ULIRGs; Díaz-Santos et al. 2017).

With our measurements and the predictions by the PDR model, we compute chi-square values for two luminosity ratios of $[\text{C\,II}]_{\text{PDR}}/\text{FIR}$ and $[\text{C\,II}]_{\text{PDR}}/\text{CO}$ in the ranges of $n_{\text{PDR}} = 10^{-3.7} \text{ cm}^{-3}$ and $G_0 = 10^{0.6-6}$. We derive the appropriate parameters of $n_{\text{PDR}} = 10^{5.3-5.75} \text{ cm}^{-3}$ and $G_0 = 10^{3.5-3.75}$ in the central 1 kpc region and $n_{\text{PDR}} = 10^{5.0-5.25} \text{ cm}^{-3}$ and $G_0 = 10^{3.25-3.5}$ in the central 3 kpc region with the confidence level of 68% (Figure 4). The central 1 kpc region likely has a higher gas density compared to the outer region, which is expected given the strong concentration of FIR emission. The physical conditions are close to those found in Galactic OB star formation regions and local ULIRGs and are also consistent with previous studies for other high-redshift SMGs (e.g., Hailey-Dunsmue et al. 2010; Stacey et al. 2010; Rybak et al. 2019). Some studies using dense gas tracers also support a high-density gas in SMGs (e.g., Danielson et al. 2011; Spilker et al. 2014; Oteo et al. 2017).

### 3.4. Gas-phase Metallicity

We have successfully measured the line ratio of [O III]/[N II] 88 $\mu$m/[N II] 205 $\mu$m in the central 3 kpc region of COSMOS-AzTEC-1 at $z = 4.3$, which is the highest redshift where both nitrogen and oxygen lines are detected. We interpret the ratio as a tracer indicator of gas-phase metallicity $Z_{\text{gas}}$ (Pereira-Santaella et al. 2017; Rigopoulou et al. 2018). However, [O III]/[N II] ratios strongly depend on the hydrogen density in ionized regions $n_{H^+}$ and the dimensionless ionization parameter $U_{\text{ion}}$, defined as $U_{\text{ion}} = \phi_{H}/n_{H^+}$, where $\phi_{H}$ is the flux of ionizing photons with $h\nu > 13.6 \text{ eV}$ and $c$ is the speed of light. In the previous sections, we derived the hydrogen density in PDRs $n_{H^+}^{\text{PDR}}$ and the flux of UV radiation $G_0$. These two parameters are closely related to $n_{H^+}^{\text{ion}}$ and $\phi_{H}$. We use the spectral synthesis code Cloudy v17.01 (Ferland et al. 2017) to calculate $n_{H^+}^{\text{PDR}}$ and $G_0$ as well as the predicted [O III]/[N II] ratio as a function of $n_{H^+}^{\text{ion}}$, $U_{\text{ion}}$, and $Z_{\text{gas}}$. We generate the input spectra of a constant star formation model with an age of 1 Myr by using the Binary Population and Spectral Synthesis (BPS) code (Eldridge & Stanway 2016; Stanway et al. 2016). We also assume that the stellar metallicity is lower than gas-phase metallicity by a factor of 5 since the duration of the extreme starburst is likely shorter than a timescale for metal enrichment by SNe Ia ($\sim$1 Gyr). Adopting models with massive star binaries and lower stellar metallicities is motivated by recent results in star-forming galaxies at $z \sim 2$ (Steidel et al. 2016). Gas element abundance patterns and other parameters in the Cloudy run are the same as the previous calculations by Nagao et al. (2011).

We find that only models with $n_{H^+}^{\text{ion}} = 10^{4.2-4.3} \text{ cm}^{-3}$ and $U_{\text{ion}} = 10^{-3.8-3.5}$ satisfy the physical conditions ($n_{H^+}^{\text{PDR}} = 10^{5.0-5.25} \text{ cm}^{-3}$ and $G_0 = 10^{3.25-3.5}$) constrained by our PDR modeling. Under the restrictions of $n_{H^+}^{\text{ion}}$ and $U_{\text{ion}}$, [O III]/[N II] ratios primarily depend on the gas-phase metallicity (Figure 5). The measured luminosity ratio of $L_{\text{[O III]/[N II]}} = 6.4 \pm 2.2$ corresponds to a near solar metallicity, $Z_{\text{gas}} = 0.7-1.0 Z_{\odot}$ in the fiducial model with $U_{\text{ion}} = 10^{-3.7}$. Given the stellar mass of $M_* \sim 10^{11} M_{\odot}$, the metallicity of galaxies decreases as a function of increasing redshift. Onodera et al. (2016) have measured the metallicities
with optical lines for star-forming galaxies at $z = 3$–4 in the main stellar mass range of $M_\star = 10^{9.3}$–$10^{10.5} M_{\odot}$, showing a positive correlation between stellar mass and metallicity (see also Maiolino et al. 2008). The extrapolation of the mass–metallicity relation at $z = 3$–4 gives $Z_{\text{gas}} \sim 1.0 Z_{\odot}$ for massive galaxies with $M_\star = 10^{11} M_{\odot}$, which is consistent with our measurement.

4. Discussion

We have reported the physical properties of the CNO fine structure lines ([C II] 158 $\mu$m, [N II] 205 $\mu$m, and [O III] 88 $\mu$m) in a bright unlensed submillimeter galaxy at $z = 4.3$, which is the highest redshift where both nitrogen and oxygen lines are detected. Our deep and high-resolution data show that the ionized, PDR, and molecular gas have similar kinematic properties. We confirm that COSMOS-AzTEC-1 is rotation-dominated with $V_{\text{max}}/\sigma_0 = 2.5$–2.8, which is close to the values for massive quiescent galaxies at $z \sim 2$ (e.g., Toft et al. 2017; Newman et al. 2018). Since these galaxy populations are likely the progenitors of the most massive slow rotators at $z = 0$ (e.g., Cappellari 2016), they have to lose significant angular momentum in the intervening time (Tadaki et al. 2017). Cosmological simulations predict that dry mergers efficiently spin down galaxies while wet mergers increase the angular momentum (e.g., Naab et al. 2014; Lagos et al. 2018). The high-redshift progenitors of slow rotators would change the kinematic properties at $z < 2$.

We have also determined the physical conditions of gas in PDRs and ionized regions with the CNO emission. Our PDR modeling indicates that most of the [C II] emission arises from dense PDRs with $n_{\text{H}}$ $\approx$ $10^5$–$5.5 \times 10^5$ cm$^{-3}$ and $G_0 = 10^{3.5}$–$3.75$, which are likely associated with massive star formation. These PDR parameters constrain the gas density in ionized regions and the ionizing flux, leading to the ionization parameters. Using the fiducial photoionization models and the measured [O III]/[N II] ratios, we find COSMOS-AzTEC-1 to be a chemically evolved system with $Z_{\text{gas}} = 0.7$–1.0 $Z_{\odot}$, which are consistent with previous studies of other dusty star-forming galaxies at high-redshift (Nagao et al. 2012; Rigopoulou et al. 2018). The 0$\arcsec$3-resolution [O III] map also gives the upper limit of $L_{[O \text{ III}]}/L_{[N \text{ II}]} < 5.7$ in the central 1 kpc region, which is not much larger than the value in the central 3 kpc region, $L_{[O \text{ III}]}/L_{[N \text{ II}]} = 6.5 \pm 2.2$. Provided that the ionization parameters are constant within the galaxy, this result would reject positive radial gradients with lower metallicity in the center as sometimes seen in star-forming galaxies at $z = 2$–4 (e.g., Cresci et al. 2010; Jones et al. 2013).

We note that our metallicity measurements are based on the assumption that ionizing sources (OB stars) are all associated with dense PDRs, motivated by the high gas density and the intense radiation field. In another extreme case that OB stars are randomly distributed with respect to the PDRs (Wolfire et al. 1990), the average ionized gas density is not necessarily connected to the gas density in individual PDR clouds. Measurements of [N II] 122 $\mu$m/$\text{[N II]} 205 \mu$m or [O III] 52/ [O III] 88 line flux ratios allow us to directly estimate the gas density in the ionized region without the assumption of geometry. In nearby star-forming galaxies, the ionized gas density is estimated to be $n_{\text{H}}^{\text{ion}} = 10^{1.2}$ cm$^{-3}$ (e.g., Herrera-Camus et al. 2016; Díaz-Santos et al. 2017), which is much lower than expected in COSMOS-AzTEC-1. The high gas density is preferred in extreme starburst galaxies, but it needs to be verified by direct measurements based on [N II] 122 $\mu$m/$\text{[N II]} 205 \mu$m or [O III] 52/[O III] 88 ratios. Ionization parameters are also another factor leading to the uncertainties of metallicity measurements. Nagao et al. (2011) find that the [O III] 88 $\mu$m/[N II] 57 $\mu$m ratio is a good tracer of the gas-phase metallicity, being weakly dependent on ionization parameters. For galaxies at $z < 4.6$, [N III] 57 $\mu$m emission are not, unfortunately, accessible with ALMA. Comparing the [N II] and [O III] lines with the radio free–free continuum would be a good test for verifying our approach through PDR modeling since it is an independent method to measure the metallicity (Herter et al. 1981; Ferkinhoff et al. 2015; Lamarche et al. 2018). In spite of these uncertainties, observations of CNO emission in SMGs would open a new avenue for understanding chemical evolution of massive galaxies in the early universe.

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References

Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, A&A, 622, A103
Bouché, N., Carfantan, H., Schröetter, I., Michel-Dansac, L., & Contini, T. 2015, AJ, 150, 92
Burgarella, D., Buat, V., & Iglesias-Páramo, J. 2005, MNRAS, 360, 1413
Cappellari, M. 2016, ARA&A, 54, 597
Casey, C. M. 2012, MNRAS, 425, 3094
Cresci, G., Mannucci, F., Maiolino, R., et al. 2010, Natur, 467, 811
Danielson, A. L. R., Swinbank, A. M., Smail, I., et al. 2011, MNRAS, 410, 1687
Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2017, ApJ, 846, 32
Diederik Eldridge, J. J., & Stanway, E. R. 2016, MNRAS, 462, 3302
Ferkinhoff, C., Brisbin, D., Nikola, T., et al. 2015, ApJ, 806, 260
Ferkinhoff, C., Hailey-Dunsheath, S., Nikola, T., et al. 2010, ApJ, 714, L147
Feilner, G. J., Chatzikos, M., Guzmán, F., et al. 2017, RMxAA, 53, 385
Gullberg, B., Swinbank, A. M., Smail, I., et al. 2018, ApJ, 859, 12

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