The prospects for observing [O iii] 52 micron emission from galaxies during the Epoch of Reionization

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ABSTRACT
The [O iii] 88 μm fine structure emission line has been detected into the Epoch of Reionization (EoR) from star-forming galaxies at redshifts $6 < z \lesssim 9$ with ALMA. These measurements provide valuable information regarding the properties of the interstellar medium (ISM) in the highest redshift galaxies discovered thus far. The [O iii] 88 μm line observations leave, however, a degeneracy between the gas density and metallicity in these systems. Here we quantify the prospects for breaking this degeneracy using future ALMA observations of the [O iii] 52 μm line. Among the current set of ten [O iii] 88 μm emitters at $6 < z \lesssim 9$, we forecast 52 μm detections at 6-σ in SXDF-NB1006-2, B14-6566, J0217-0208, and J1211-0118 within on-source observing times of 2-10 hours, provided their gas densities are larger than about $n_H \gtrsim 10^2 - 10^3$ cm$^{-3}$. Other targets generally require much longer integration times for a 6-σ detection. Either successful detections of the 52 μm line, or reliable upper limits, will lead to significantly tighter constraints on ISM parameters. The forecasted improvements are as large as $\sim 3$ dex in gas density and $\sim 1$ dex in metallicity for some regions of parameter space. We suggest SXDF-NB1006-2 as a promising first target for 52 μm line measurements.

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

1 INTRODUCTION

Recent ALMA observations of atomic fine structure emission lines have provided spectroscopic redshifts for galaxies into the EoR at $6 < z \lesssim 9$ and started to probe their ISM properties (e.g., Willott et al. 2015; Inoue et al. 2016; Marrone et al. 2018). Specifically, these measurements constrain the internal structure, dynamics, ionization state, and gas phase metallicity in some of the first galaxies. The fine structure line observations can be further combined with rest-frame ultraviolet (UV) estimates of the star-formation rates (SFRs) in these galaxies and infrared (IR) determinations of stellar mass, allowing one to study correlations between gas content and stellar populations into the EoR. These, in turn, give crucial empirical guidance for models of galaxy formation and help to determine the properties of the sources that reionized the universe. More specifically, this letter focuses on [O iii] fine-structure emission lines from the EoR, which probe the gas phase metallicity and density in the HII regions in these galaxies. First, these observations help in understanding the chemical enrichment history in early galaxy populations. Furthermore, in lower redshift galaxy samples, there is a well-established correlation between gas phase metallicity and stellar mass (Lequeux et al. 1979; Tremonti et al. 2004): this is thought to reflect the impact of outflows which drive gas and metals out of the shallow potential wells of small mass galaxies but have less affect in larger galaxies. The recent [O iii] measurements, combined with stellar mass estimates, start to study whether these correlations hold and/or evolve into the EoR (Jones et al. 2020). Next, the gas density measurements are relevant for understanding the internal structure and escape fraction of ionizing photons from these galaxies (e.g. Benson et al. 2013; Kimm & Cen 2014; Ma et al. 2015; Kimm et al. 2019). The escape fraction plays a critical, yet highly uncertain, role during cosmic reionization.

Thus far, ALMA has detected the [C ii] and [O iii] 158 micron emission line and the [O iii] 88 micron line from tens of $6 < z \lesssim 9$ galaxies (e.g., Pentericci et al. 2016; Laporte et al. 2017; Carniani et al. 2017; Smit et al. 2018; Carniani et al. 2018a,b; Hashimoto et al. 2018, 2019; Tamura et al. 2019; Harikane et al. 2020; Novak et al. 2019). Intriguingly, in some cases the [O iii] luminosities from this sample exceed those of local galaxies (De Looze et al. 2014) with the same SFRs (Moriwaki et al. 2018). The ratio between the [O iii] 88 μm and [C ii] luminosity is also larger than in local galaxies (Harikane et al. 2020). In short, the [O iii] 88 μm line is a bright and promising tracer of reionization-era galaxies.

Motivated by the ALMA [O iii] 88 μm detections and their future promise, we developed a first-principles analytic model for [O iii] emission in Yang & Lidz (2020), (hereafter Yang2020). We leave the more complex modeling required for studying [C ii] emission (e.g. Ferrara et al. 2019; Katz et al. 2019) to future work. The
Yang2020 model determines the [O iii] luminosity from galaxies with a given SFR, metallicity, gas density, and ionizing spectral shape. Briefly, in these calculations we first compute the total volume in HII regions across each galaxy and the [O iii] fraction within these regions. Then we determine the level populations in the different fine-structure states and the resulting line luminosities. We cross-checked these calculations against CLOUDY simulations and find that they agree to better than 15% accuracy across a broad range of model parameters. We then applied the model to derive bounds on the gas phase metallicity and density in the HII regions from the current ALMA sample of 88 µm detections and measurements of their luminosity to SFR. (This is denoted herein as $L_{10}/$SFR since the 88 µm transition is between the first excited level and the ground state, i.e. it is a $1 \rightarrow 0$ transition).

An important degeneracy is left, however, between the metallicity and gas density from the 88 µm and SFR measurements alone (Yang2020). At high densities, $n_{\text{H}} \gtrsim 10^2 - 10^3$ cm$^{-3}$, collisional de-excitations become important and it is impossible to distinguish galaxies with high density and metallicity from those with lower density and metallicity, since the line luminosity drops with increasing density and/or decreasing metallicity. The 88µm and SFR measurements alone yield only an upper bound on gas density, $n_{\text{H}}$, and a lower bound on metallicity, $Z$.

Here we forecast the prospects for breaking this degeneracy using future ALMA measurements of the [O iii] 52 µm transition. This line arises from transitions between the second excited and first excited fine structure levels in [O iii] (and so the luminosity in this line is denoted hereafter as $L_{21}$). The ratio between the 52 µm and 88 µm emission ($L_{21}/L_{10}$) provides a powerful density diagnostic (e.g. Draine 2011), since the lines have different critical densities and their ratio hence depends on the importance of collisional de-excitations. As the energy splitting between these fine-structure states is small compared to the temperature of the HII region gas, the line ratio is insensitive to the temperature of the gas. Further, the lines arise from the same ion and so the ratio does not depend on the ionization state of the gas, nor appreciably on its metal content.

We use the ALMA sensitivity calculator\footnote{https://almascience.eso.org/proposing/sensitivity-calculator} to determine the expected signal-to-noise ratio (SNR) for future [O iii] 52 µm measurements alone. We use the Yang2020 model to explore the range of possibilities here and to characterize the improved parameter constraints that will be enabled by future 52 µm measurements.

### 2 DATA

We consider the sample of nine ALMA [O iii] 88 µm detections plus one upper limit at 6 $< z < 9$, published in the current literature, and summarized in Table 1. These include one gravitationally-lensed galaxy at $z = 9.1$ (Hashimoto et al. 2018) (MACS1149-JD1), a lensed Y-band drop-out galaxy A2744_YD4 at $z \sim 8$ (Laporte et al. 2017), and the $z \sim 8$ Y-dropout Lyman break galaxy (LBG), MACS0416_Y1 (Tamura et al. 2019). At $z \sim 7$, [O iii] from one Lyα emitter is detected in a follow up measurement carried out by Inoue et al. (2016). In addition, the LBG B14-65666 is measured by Hashimoto et al. (2019), and the star forming galaxy BDF-3299 is detected in Carniani et al. (2017), each near $z \sim 7$. Three luminous LBGs, J1211-0118, J0235-0532, and J0217-0208 at $z \sim 6$ are presented by Harikane et al. (2020). Finally, a non-detection of [O iii] from the Lyα emitting galaxy z7_GSD_3811 at $z = 7.7$ is reported in Binggeli et al. (2020).

### 3 MODEL

Our aim is to forecast the expected SNR for 52 µm emission line observations of this sample of galaxies as well as the improvements expected for the ISM parameter constraints. In order to do this we need to account for current uncertainties in the [O iii] 88 µm luminosities and SFRs, and we also need to span the allowed ISM parameter space.

To accomplish this, we turn to the Yang2020 [O iii] emission model. In brief, this model treats the ionizing output of each galaxy as concentrated into a single effective source of ionizing radiation at the center of a spherically symmetric HII region, which is in photo-ionization equilibrium. The rate of hydrogen ionizing photons emitted by this source is given by $Q_{\text{HII}}$ and is determined by the galaxy’s SFR, stellar metallicity, and initial mass function (IMF). Although in reality the [O iii] emission arises from a complex ensemble of discrete HII regions distributed across the galaxy, our simplified treatment – with a single effective HII region – should provide an accurate prediction of the total [O iii] luminosity summed over all of the HII regions in the galaxy. We adopt a STARBURST99 population synthesis stellar spectrum (Leitherer et al. 1999) with a continuous SFR, a Salpeter IMF (Salpeter 1955), and an age of 10 Myr throughout, in which case the doubly-ionized oxygen fraction is close to unity throughout the HII region for the SFRs considered here. As discussed in Yang2020, we don’t expect the precise choice of stellar spectrum here to significantly impact our results. For simplicity in making our forecasts we ignore variations in the gas density and metallicity across each galaxy (see Yang2020 for extensions to this and further discussion). In this case the gas density is characterized by a single number, $n_{\text{H}}$, across each galaxy, while the metallicity is described by the parameter $Z$. We further assume that the gas phase and stellar metallicities are identical in what follows. The Yang2020 model then solves for the fine structure level populations in the three-level atom approximation, accounting for radiative de-excitations, collisional excitations and de-excitations, and sub-dominant radiative trapping effects (computed in the escape probability approximation; these effects are unimportant for plausible [O iii] velocity distributions).

Under these assumptions, the luminosity in the [O iii] 88µm line ($L_{10}$) and the 52 µm luminosity ($L_{21}$) may be written as:

$$L_{ij} = \frac{R_i}{1 + R_1 + R_2} \left( \frac{n_{\text{O}}}{n_{\text{H}}^2} \right) Z \frac{A_{ij}}{Z_{\odot}} \frac{\nu_{ij} Q_{\text{HII}}}{\alpha_{\text{HII}} \Omega_{\text{HII}}}. \tag{1}$$

Here $R_i$ is the fractional abundance of OIII ions in the i-th energy state and $(n_{\text{O}}/n_{\text{H}}^2)_{\odot} = 10^{-3.31}$ is the solar oxygen to hydrogen abundance ratio. The quantity $A_{ij}$ is the Einstein-A coefficient, specifying the spontaneous decay rate from the i-th to the j-th energy level. The optical depth, $\tau_{ij}$, is treated self-consistently in the escape probability approximation but is unimportant in practice. Here $\nu_{ij}$ is the rest-frame frequency of the corresponding [O iii] emission line, $\alpha_{\text{HII}}$, is the case B recombination rate of hydrogen, and $n_e$ is the number density of free electrons. This formula then connects the luminosity in each line to the ISM parameters, $n_{\text{H}}$ and $Z$.

Yang2020 used this analytic model to constrain the ISM properties of nine ALMA targets with the $L_{10}$/SFR observations. As
discussed earlier, this left a degeneracy between gas density and metallicity (see also Figure 2). This can be broken by adding [O iii] 52 μm measurements, owing to the different critical densities of the two lines. It is instructive to examine the asymptotic behavior of the line ratio, as discussed in Yang2020:

\[
\frac{L_{21}}{L_{10}} = \left\{ \begin{array}{ll}
\frac{k_{g2}}{k_{g1}} \frac{\nu_{21}}{\nu_{10}} & \approx 0.55 \quad \text{if } n_e \to 0; \\
\frac{g_2}{g_1} \frac{A_{21} \nu_{21}}{A_{10} \nu_{10}} = 10.71 \quad \text{if } n_e \to \infty,
\end{array} \right.
\]

where \(g_2 = 5\) and \(g_1 = 3\) are the degeneracies of the \(^3\)P\(_2\) ("2") and \(^1\)P\(_1\) ("1") levels. The \(k_s\) are OIII collisional excitation rates. The low-density limit has a slight temperature dependence, but this is weak since the energy separation between these states is small relative to the HI region temperature. The number given in Eq 2 assumes a gas temperature of \(T = 10^4\) K. To further illustrate, Figure 1 shows the line ratio across the \(\log n_H - \log Z\) parameter space assuming \(Q_{\text{HI}} = 10^{44}\) s\(^{-1}\) and \(T = 10^4\) K. The luminosity ratio transitions between the low and high density limits of Eq 2 with a relatively sharp increase between \(10^2 \lesssim n_H \lesssim 10^3\) cm\(^{-3}\), above which the 52 μm line is more luminous. The ratio is almost independent of metallicity, with only a weak dependence from the fact that the number density of free electrons depends slightly on Z. There is also a small effect that arises because the gas temperature depends on metallicity (see Yang2020 Eq 2); this is not captured in Figure 1, which adopts a fixed temperature, but is included in our modeling.

Using the \(n_H - Z\) constraints in Yang2020, determined from the \(L_{10}/SFR\) measurements in the literature, we identify the currently allowed range in \(L_{21}/L_{10}\) for each of the ten ALMA galaxies. The 68% confidence interval for this quantity is reported in column (6) of Table 1.

### 4 OBSERVING TIME

We now turn to compute the expected SNR for future ALMA 52 μm observations. We determine the ALMA sensitivity for a 10-hour measurement as well as the on-source observing time required to achieve a SNR of 6 [O iii] 52 μm detection at peak flux density for each target under different \(L_{21}/L_{10}\) scenarios. Specifically, we consider the minimum and maximum \(L_{21}\) allowed by the Yang2020 constraints at 68% confidence, as well as an average between these two luminosity limits. In order to compute the ALMA sensitivity for each of the ten targets in Table 1 we use the ALMA Sensitivity Calculator web interface. We assume a Gaussian line profile for each emission line and that the full-width-at-half-maximum (FWHM) of the 52 μm line matches the best fit observational line width of its 88 μm counterpart. We adopt the 43 ALMA antenna configuration and frequency channels of width set by the FWHM/3, such that each spectral line is resolved by three channels. The ALMA band containing the 52 μm line for each target is listed in column (5) of Table 1. The resulting 1-σ noise on the integrated 52 μm luminosity for a 10-hour on-source measurement is given in column (7). Finally, the

![Figure 1](image.png)
on-source integration times required for 6-σ detections are shown for the maximum, mean, and minimum L$_{21}$ cases in column (8).

Among the ten targets studied in this work, the 52 µm line emitted by MACS1149-JD1 is not observable by ALMA because its observed 52 µm frequency falls in the gap between the band 8 and band 9 windows. The other nine targets are in principle observable. The atmospheric opacity is, however, very large at the observed frequencies of the 52 µm line for A2744-YD4, MACS0416-Y1, and BDF-3299 and so it is not feasible to detect these objects in practice. If the galaxies in this data set tend to have high gas densities, n$_{HI}$ ≥ 10$^{2} – 10^{3}$ cm$^{-3}$; then the [O III] 52 µm lines from SXDF-NB1006-2, B14-65666, J0217-0208, and J1211-0118 can be detected within 10 hours. At low gas densities, the 52 µm emission line is significantly harder to detect and it may be possible to place only upper limits on the luminosity of this line. Nevertheless, even in the low density case where the 52 µm line is almost a factor of 2 less luminous than the 88 µm emission, J0217 is still theoretically detectable within 24 hours of on-source integration time. In the intermediate density case (where we take L$_{21}$ = L$_{21}$×((L$_{21}$/L$_{10}$)$_{max}$ + (L$_{21}$/L$_{10}$)$_{min}$)/2), we find that 6-σ detections are possible in less than 10 hours for SXDF-NB1006-2 and B14-65666. In the high and intermediate density cases, SXDF-NB1006-2 requires the least time for a significant detection (~2–6 hours). Therefore, we suggest SXDF-NB1006-2 as a promising first target for an ALMA 52 µm follow-up measurement.

5 52 µM MEASUREMENT AND ISM PARAMETER CONSTRAINTS

Figure 2 shows forecasts for how the parameter constraints in the log n$_{HI}$ – log Z plane will improve after including L$_{21}$/L$_{10}$ measurements. Specifically, we select the four most promising targets from Table 1: SXDF-NB1006-2, B14-65666, J0217-0208, and J1211-0118 and consider 10 hour on-source integration times for the 52 µm followup observations (see column (7) of Table 1 for the resulting noise estimates.) These forecasts are combined with the constraints obtained in Yang2020 from the L$_{10}$/SFR measurements of Harkane et al. (2020) (grey regions in the figure). In each case, we adopt a hard metallicity prior enforcing Z ≤ Z$_{0}$. As in the previous section, we explore the constraints expected for three different assumptions regarding the line ratio L$_{21}$/L$_{10}$. We assume a Gaussian likelihood for the line ratio, the standard error propagation formula to compute the uncertainties on this ratio from the independent luminosity measurement errors, and Monte Carlo Markov Chain (MCMC) calculations to forecast the expected parameter constraints. The top row of Figure 2 shows the maximal case, the middle row the intermediate scenario, and the bottom row gives the minimum line ratio model calculations. The forecasted constraints from the line ratio alone are shown by the red regions/lines in Figure 2, while the combined constraints are given in blue.

As discussed earlier, the L$_{10}$/SFR measurements alone leave a strong degeneracy between gas density and metallicity, giving rise to the “L”-shaped grey regions in the figure. The 52 µm line ratio measurements will add nearly horizontal ellipses in the log n$_{HI}$ – log Z plane through their sensitivity to the gas density. The three cases show the impact of shifting the fiducial gas density from a higher value to a lower value as one moves from the top row to the bottom one. Note that in some examples these constraint forecasts come only from upper limits on the 52 µm line emission: for the minimum L$_{21}$/L$_{10}$ case we do not expect 6-σ line detections towards any of the four targets in less than ten hours. Further, for the intermediate L$_{21}$/L$_{10}$ model, J0217-0208 and J1211-0118 still fall below the SNR=6 threshold. Those examples illustrate that even an upper limit will help to constrain the parameter space here.

In most cases, we forecast that the gas density posteriors will tighten significantly after including 52 µm follow-up measurements. In many of the examples shown this should also help to tighten the metallicity constraint by breaking the degeneracy between density and metallicity. For instance, in the maximal line ratio case it will be possible to decisively show that SXDF-NB1006-2 has a high metallicity Z ≥ 0.092Z$_{0}$ at 95% confidence, while based on L$_{10}$/SFR alone this galaxy’s metallicity may be as low as Z = 0.011Z$_{0}$, again at 95% significance. The improvements forecast are weakest for the case of J0217-0208. This galaxy has a very large L$_{10}$/SFR and so high densities are already excluded for this system (at least under our Z ≤ Z$_{0}$ prior). Nevertheless, we expect the gas density determination to improve for this galaxy although the metallicity constraint will not tighten. Overall, the prospects for obtaining more stringent ISM parameter constraints from 52 µm observations towards several of the galaxies in the current sample appear promising. In addition, we expect that further 88 µm detections will extend the list of promising targets here in the near future.

6 CONCLUSION

We have forecast the prospects for detecting the [O III] 52 µm emission line from the current sample of ten ALMA [O III] 88 µm measurements towards galaxies at 6 < z ≤ 9. Adding 52 µm detections or upper limits will break the degeneracy between gas density and metallicity that remain from 88 µm and SFR measurements alone.

Using the Yang2020 model we forecast that the [O III] 52 µm lines from SXDF-NB1006-2, B14-65666, J0217-0208, and J1211-0118 can be detected within 10 hours of on-source observing time, provided these galaxies have gas densities larger than n$_{HI}$ ≥ 10$^{2} – 10^{3}$ cm$^{-3}$. We forecast the parameter space improvements that will be possible for the four most promising targets, SXDF-NB1006-2, B14-65666, J0217-0208, and J1211-0118, with a ten hour ALMA 52 µm measurement. We find that the gas density constraint should tighten by 1-3 dex for these sources, while the metallicity posterior will narrow by as much as 1 dex for SXDF-NB1006-2, B14-65666, and J1211-0118. We identify SXDF-NB1006-2 as the most favorable target for first followup observations. The 52 µm measurements should help us understand the gas density and metallicity of some of the first galaxies. These observations will help determine the internal structure of high redshift galaxies and in probing the mass metallicity relationship in the sources that reionized the universe.

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2 In this work log denotes a base-10 logarithm.

3 For example, the ALMA Large Program REBELS (2019.1.01634.L) aims to discover the most luminous [C II] and [O III] galaxies in the EoR.
Figure 2. Forecasted improvements on gas density-metallicity parameter constraints from combining current $L_{10}/$SFR measurements with upcoming redshifted 52 $\mu$m observations in four example galaxies, SXDF-NB1006-2, B14-65666, J0217-0208, and J1211-0118 (see Table 1). In each panel, the grey regions and lines show the constraints from the current $L_{10}/$SFR measurements, the red regions and lines show forecasts for the 52 $\mu$m line detections alone, while the blue regions and lines give the joint constraints that will be possible. The upper/middle/lower rows show results for the maximum/average/minimum $L_{21}$ scenarios (see text). The shaded regions give 68% and 95% confidence intervals.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

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