Star formation law in the EoR from [CII] and CIII] lines

L. Vallini1,*, A. Ferrara1, A. Pallottini2,3, S. Carniani2, S. Gallerani2
1Leiden Observatory, Leiden University, PO Box 9500, 2300 RA Leiden, The Netherlands
2Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy
3Centro Fermi, Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Piazza del Viminale 1, Roma, 00184, Italy

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
We present a novel method to simultaneously characterize the star formation law and the interstellar medium properties of galaxies in the Epoch of Reionization (EoR) through the combination of [CII]158μm (and its known relation with star formation rate) and CIII]λ1909Å emission line data. The method, based on a Markov Chain Monte Carlo algorithm, allows to determine the target galaxy average density, n, gas metallicity, Z, and “burstiness” parameter, κ, quantifying deviations from the Kennicutt-Schmidt relation. As an application, we consider COS-3018 (z = 6.854), the only EoR Lyman Break Galaxy so far detected in both [CII] and CIII]. We show that COS-3018 is a moderate starburst (κ ≈ 3), with Z ∼ 0.4 Z⊙, and n ∼ 500 cm−3. Our method will be optimally applied to joint ALMA and JWST targets.

Key words: galaxies: ISM – galaxies: high-redshift – ISM: photodissociation region

1 INTRODUCTION
How do galaxies convert their gas into stars? How do their interstellar medium (ISM) properties influence star formation? Answers to these questions hold the key to understand galaxy evolution (Dayal & Ferrara 2018, for a review).

In nearby galaxies and at intermediate redshifts, the so-called Kennicutt-Schmidt (KS) law (Schmidt 1959; Kennicutt 1998; de los Reyes & Kennicutt 2019), relating the star formation rate and the gas surface density is well established. Dozens of observational studies ranging from the local Universe (e.g. Bigiel et al. 2008; Schruba et al. 2011) up to z > 3 (e.g. Daddi et al. 2010; Tacconi et al. 2013; Genzel et al. 2015; Hodge et al. 2015) have shown that, when averaged over kpc-scales, the star formation rate, SFR, and the cold gas, Σgas, surface density in disk galaxies follow a tight relation,

Σ_{SFR} = 10^{-12} \kappa \Sigma_{g}^{3/2}, \quad (n \approx 1.4) \tag{1}

valid over about five dex in Σgas (Heiderman et al. 2010). Two different SF regimes can be identified in the Σ_{SFR}−Σ_{gas} plane: “quiescent” (κ ≈ 1) and “starburst” (κ > 1) galaxies (Daddi et al. 2010; Hodge et al. 2015). However, as we move towards the Epoch of Reionization (EoR, z > 6), a precise assessment of the KS relation becomes progressively more difficult or even impossible. Advanced optical/near-infrared facilities such as the Hubble Space Telescope (HST), Very Large Telescope (VLT), Keck, and Subaru telescopes enabled rest-frame ultraviolet (UV) continuum and line emission detection in large samples of EoR galaxies (e.g. Bouwens et al. 2015). The exquisite spatial resolution of such instruments often allows to carry out UV size measurements (e.g. Shibuya et al. 2015; Curtis-Lake et al. 2016; Bowler et al. 2017; Kawamata et al. 2018; Matthee et al. 2019), hence enabling estimates of Σ_{SFR} in EoR galaxies.

Spatially-resolved detections of cold gas tracers such as CO lines in these systems are instead still very challenging or lacking (e.g. Vallini et al. 2018; D’Odorico et al. 2018; Pavesi et al. 2019). Low-J (J ≤ 3) CO rotational transitions are hard to detect in quiescent star-forming galaxies and are still limited to z ∼ 3 (Tacconi et al. 2013; Genzel et al. 2015) while at 3 < z < 4.5 only few significant detections have been reported, either in massive sub-millimeter galaxies (Hodge et al. 2015; Sharda et al. 2018, 2019) or strongly lensed systems (Coppin et al. 2007; Dessauges-Zavadsky et al. 2015). Beside CO, alternative tracers such as the [CII]158μm emission, calibrated at z ≈ 1, have been proposed to measure the gas mass (Zanella et al. 2018). However, Pavesi et al. (2019) pointed out that a full characterization of the ISM in EoR galaxies requires, in addition to [CII], information on CO or a ionized gas tracer.

In the last years ALMA (Carilli & Walter 2013) has opened a new window on the ISM properties of early galaxies, allowing for the first time the detection at high spatial resolution and sensitivities of the 158μm 2P_{3/2} → 2P_{1/2} transition of ionized carbon ([CII]) (e.g. Maiolino et al. 2015; Capak et al. 2015; Smit et al. 2018; Carniani et al. 2018;
Hashimoto et al. 2019; Matthee et al. 2019). [CII] is the most luminous line in the far-infrared (FIR) band (Hollenbach & Tielens 1999), and traces cold neutral/molecular gas associated with Photo Dissociation Regions (PDR) (e.g. Vallini et al. 2015; Pallottini et al. 2017; Ferrara et al. 2019).

Importantly, the James Webb Space Telescope (JWST) will soon provide a complementary probe of the high-z ISM, targeting rest-frame optical/UV emission lines associated with ionized gas. Among the various UV line tracers, current state-of-the-art observational campaigns with e.g. VLT and KECK (e.g. Stark et al. 2015, 2017; Ding et al. 2017; Laporte et al. 2017; Mainali et al. 2018; Hutchison et al. 2019) and theoretical studies (Feltre et al. 2016; Jaskot & Ravindranath 2016; Nakajima et al. 2018) showed that low-metallicity, $z > 5$ galaxies are expected to show prominent C III]1909Å line emission. Such line will be likely detected in large samples of galaxies with JWST, opening an interesting synergy with ALMA in targeting carbon lines. In this work we show that, by combining [CII]158μm and CIII]λ1909Å data it is possible to constrain at the same time the KS relation and ISM properties of EoR galaxies. After presenting the method in Sec. 2, in Sec. 3 we apply it to COS-3018555981 at $z = 6.854$, the only Lyman Break Galaxy (LBG) representative of quiescent star-forming galaxies so far detected at $z > 6.5$ in [CII] and CIII]. In Sec. 4 we discuss the implications of the results and our conclusions.

2 METHOD

Our method is based on an extension of the physical model for the [CII] emission in galaxies presented in Ferrara et al. (2019, F19 hereafter). While locally a tight $\Sigma_{[CII]}-\Sigma_{[CIII]}$ correlation has been measured (De Looze et al. 2014; Herrera-Canal et al. 2015), many EoR galaxies show $\Sigma_{[CII]}$ values almost systematically fainter than expected from their measured $\Sigma_{[CIII]}$ (Carniani et al. 2018; Pallottini et al. 2019).

F19 argued that three factors can produce such deficit: (a) a high “burstiness” parameter $\kappa_s$ (see eq. 1); (b) a low gas density $n_c$; (c) a low metallicity, $Z$, with (b) and (c) playing a sub-dominant role. If a third observed quantity, beside $\Sigma_{[CII]}$ and the deviation, $\Delta_{[CII]}$, from the local $\Sigma_{[CII]}-\Sigma_{[CIII]}$ relation is available, then the $n_c, Z, \kappa_s$ degeneracy can be broken, thus enabling a complete characterization of the ISM properties and star formation law in EoR galaxies.

CIII] is an excellent additional candidate line to break the degeneracy. In fact, contrary to the [CII] line, its luminosity at fixed $\Sigma_{[CIII]}$ grows with $\kappa_s$ due to the progressively thicker ionized layer (F19). Moreover, the $\Sigma_{[CIII]}/\Sigma_{[CII]}$ ratio is unaffected by the (unknown) relative abundances of different elements at high-$z$. In what follows we summarize the basic equations of our model, and operationally define $\Delta_{[CII]}$. We refer the interested reader to F19 for a complete derivation of the equations.

2.1 [CII] emission model

Consider a disk galaxy with mean gas density $n_c$, carbon abundance $A_C = 2.7 \times 10^{-4}$ (Asplund et al. 2009), metallicity $Z$, and ionization parameter $U = n_e/n_c$. The [CII] surface brightness [erg cm$^{-2}$], can be written (F19, eq. 35) as:

$$\Sigma_{[CII]} = 2.4 \times 10^5 F_{[CII]}(n, Z, U)$$

where $F_{[CII]} = f_{[CII]} + f_{[CII]}(\text{in erg s}^{-1} \text{cm}^{-2})$ is the emerging [CII] flux. The first term in the previous equation accounts for the emission due to collision of C$^+$ ions with $e^-$ in the ionized layer:

$$f_{[CII]} = n_e \Lambda_4(5) Z A_C N_{HI}(Z, U),$$

where $n_e \approx n$ is the number density of free electrons, $\Lambda_4(T = 10^5 K) = 1.2 \times 10^{-21}$ erg cm$^3$ s$^{-1}$ is the cooling rate (Appendix B, F19), and $N_{HI} \approx A_C Z N_{D}$ is the C$^+$ column density in the ionized layer. The second term, $f_{[CII]}$, accounts for the emission due to collisions with H atoms in the neutral ($T = 10^5 K$) part of the Photo Dissociation Region (PDR):

$$f_{[CIII]} = n_0 A_4(5) A_C Z N_{PDR}(Z, U).$$

In the previous equation, $n_0$ is the H I number density; $A_4(2) = 7.65 \times 10^{-24}$ erg cm$^3$s$^{-1}$ is the collisional cooling rate (Appendix B, F19), and the C II column density is $N_{CII} \approx A_C Z N_{D}$. In Eq. 3-4, $N_{HI}$ and $N_{PDR}$ depend on the dust shielding of the intensity (parametrized by $U$) of the ionizing interstellar radiation field. We assume a constant dust-to-gas ratio, so that the dust column density providing the extinction is $\propto Z$. Rewrite eq. 15 of F19 in terms of these two quantities:

$$N_{HI} = 3.7 \times 10^{17} \ln \left(1 - \frac{1 + 59ZU}{1 + 21.7ZU}\right);$$

also use eq. 30 of F19 to write

$$N_{PDR} = \min \left[\frac{1.7 \times 10^{21}}{Z} \ln \left(1 + \frac{10^5U}{1 + 0.92Z^{1/2}}\right), N_0\right] - N_i,$$

where $N_0$ is the disk total gas column density, and

$$N_i = 1.7 \times 10^{21} Z^{-1} \ln \left(1 + 59ZU\right),$$

is the ionized layer column density (eq. 14, F19). Finally, $U$ can be related to the gas surface density, $\Sigma_{gas} = 7.5 \times 10^5 N_{H,22} M_8$ kpc$^{-2}$ (F19), and to $\Sigma_{[CII]}$ as

$$U = 1.7 \times 10^{14} \frac{\Sigma_{[CII]}}{\Sigma_9^2} \approx 10^{-3} n_s^{10/7} \kappa_s^{3/7} \Sigma_{[CIII]}\Sigma_{[CIII]} - \Sigma_{[CIII]}\Sigma_{[CIII]}.$$

where we substituted the KS relation (eq. 1) to extract the dependence on $\kappa_s$. From Eq. 2 we then predict the $\Sigma_{[CII]} - \Sigma_{[CIII]}$ relation for a given set $(n_c, Z, \kappa_s)$:

$$\Sigma_{[CII]} = 2.4 \times 10^9 F_{[CII]}(\Sigma_{[CII]}(n, Z, \kappa_s)).$$

2.2 CIII] emission model

Following the same reasoning outlined in Sec 2.1, the CIII] surface brightness can be written as:

$$\Sigma_{[CIII]} = 2.4 \times 10^9 F_{[CIII]}(n, Z, U).$$

The CIII] emission is produced by collisional excitation of C$^+$ ions by free electrons. Hence,

$$F_{[CIII]} = n_e \Lambda_{[CIII]} Z A_C N_{CIII}(Z, U),$$

1 The [CII] flux obtained with the above analytical model has been shown to be in excellent agreement with CLOUDY (Ferland et al. 2017) full RT calculations (Fig. 3, F19).
where the cooling rate at \( T = 10^4 \, K \) \( \Lambda^{(4)}_{\text{CII}} = 5.8 \times 10^{-22} \, \text{erg cm}^{-s} \, \text{s}^{-1} \) (Appendix B, F19), the \( C^{+} \) column density is \( N_{\text{CII}} \simeq A_{\lambda} Z N_{\lambda} \), with \( N_{\lambda} \) as in in Eq. 7. Use Eq. 10 to predict the \( \Sigma_{\text{CII}} - \Sigma_{\text{SF}} \) relation for a given set \((n, Z, \kappa)\):

\[
\Sigma_{\text{CII}} = 2.4 \times 10^9 F_{\text{CII}}(\Sigma_{\text{SF}}|n, Z, \kappa). \tag{12}
\]

### 2.3 Deviations from the local \( \Sigma_{\text{CII}} - \Sigma_{\text{SF}} \) relation

In the local Universe a well-assessed \( \Sigma_{\text{CII}} - \Sigma_{\text{SF}} \) relation is found in spiral (Herrera-Camus et al. 2015) and low-metallicity dwarf galaxies (De Looze et al. 2014). In the last few years, the extension of such relation to EoR galaxies has become feasible thanks to the high spatial resolution of ALMA observations. As noted by e.g., Carniani et al. (2018) and F19, of the sources at \( z > 5 \) are found to have \( \Sigma_{\text{CII}} \) Values fainter than expected on the basis of the local relation. In what follows, we will adopt the following functional form of the \( \Sigma_{\text{CII}} - \Sigma_{\text{SF}} \) relation,

\[
0.93 \log \Sigma_{\text{CII}}^{\text{local}} = \log \Sigma_{\text{SF}} + 6.99, \tag{13}
\]

which has a small 1\( \sigma \) dispersion of 0.32 dex. This is obtained by De Looze et al. (2014) for low-metallicity dwarf galaxies. We checked that using a different relation (e.g. Herrera-Camus et al. 2015) does not affect our results. These systems are usually considered to be fair analogs of reionization sources. We define the expected deviation from the local \( \Sigma_{\text{CII}} \) relation (at fixed \( \Sigma_{\text{SF}} \)) as

\[
\Delta_{\text{CII}}(\Sigma_{\text{SF}}|n, Z, \kappa) \equiv \log \Sigma_{\text{CII}} - \log \Sigma_{\text{CII}}^{\text{local}}. \tag{14}
\]

Note that \( \Delta_{\text{CII}} \) is a function of the three parameters \((\kappa, n, Z)\). As a caveat, it is worth stressing that: (i) in some cases the complex morphology of early galaxies (e.g. Kohandel et al. 2019) makes the determination of the actual size of the \( \text{CII} \) emitting region somewhat challenging; (ii) in the local \( \Sigma_{\text{CII}} - \Sigma_{\text{SF}} \) calibration, the SF is obtained both by optical lines (e.g. H\( \alpha \)) and the FIR continuum. On the contrary, the \( \Sigma_{\text{SF}} \) in EoR galaxies is often derived from the UV continuum only, as the majority of high-z sources are undetected in dust continuum, and those detected have only one point on the dust continuum SED. This makes the determination of the total infrared luminosity highly dependent on the unknown dust temperature (Behrens et al. 2018).

### 2.4 Parameters derivation

Eq. 9, 12, and 14 allow us to solve for the three unknown parameters \((\kappa, n, Z)\). Our solution method is based on a Bayesian Markov Chain Monte Carlo (MCMC) framework. We use the \( \chi^2 \) likelihood function to fit the observed \( \Sigma_{\text{CII}} \), \( \Sigma_{\text{CII}}^{\text{local}} \), and \( \Delta_{\text{CII}} \) of a galaxy and determine the posterior probability distribution of the model parameters. This choice enables us to fully characterise any potential degeneracies between our model parameters, while also providing the individual probability distribution functions (PDFs) for each of them. In this work we use the open-source \texttt{exce} Python implementation (Foreman-Mackey et al. 2013) of the Goodman & Weare’s Affine Invariant MCMC Ensemble sampler (Goodman & Weare 2010).

| Quantity | Value | Reference |
|----------|-------|-----------|
| \( r_{\text{CII}} \) (kpc) | 2.6 \pm 0.5 | This work |
| \( \Sigma_{\text{CII}}^{(n)}(L_{\odot}) \) | (2.2 \pm 0.7) \times 10^2 | This work |
| \( L_{\text{CII}}^{(n)}(L_{\odot}) \) | (1.9 \pm 0.4) \times 10^4 | (3) |
| \( \Sigma_{\text{CII}}^{(n)}(L_{\odot}) \) | (3.7 \pm 0.4) \times 10^7 | |
a reasonable assumption as CIII] and UV continuum trace ionized gas, and the CIII] 1D spectrum is extracted from the UV emitting region. All quantities are presented in Tab. 1.

From the MCMC procedure we derive the best-fit \((\kappa_s, n, Z)\) values and confidence intervals for COS-3018. We run emcee with 100 random walkers exploring the parameter space for \(5 \times 10^4\) chain steps. The chains have been initialise by distributing the walkers in a small region around \(Z = 0.2 Z_\odot, \log(n/\text{cm}^{-3}) = 2.5\) and \(\kappa_s = 1\). The \(Z = 0.2 Z_\odot\) value is equal to that assumed by Bowler et al. (2014) for the stellar metallicity in their SED fitting of COS-3018. As a caveat we note that differences between stellar and gas metallicities are likely to occur in high-z systems (Steidel et al. 2016).

We assume uniform priors for the gas density in the range \(1.0 \leq \log(n/\text{cm}^{-3}) < 3.3,\) metallicity \(0.05 < (Z/Z_\odot) \leq 1.0,\) and burstiness parameter \(0.1 \leq \kappa_s \leq 50.\) To estimate the effective number of independent samples we calculate the \(n_{\text{burn}}\) steps necessary to ensure chain independence. We adopt \(n_{\text{burn}} = 50 \tau,\) where \(\tau = 147\) is the average auto-correlation time in chain steps computed with the built-in implementation given in emcee\(^3\). Next, we discard the burn-in chunk and use the remaining portion to sample the posterior probability. The mean acceptance fraction is 0.504. For the best fit parameters and confidence levels we use the median and the 16th, 84th percentiles of the marginal PDFs (Foreman-Mackey et al. 2013).

The result of the MCMC analysis is shown in Fig. 1. The best fit gas density in COS-3018 is \(\log(n/\text{cm}^{-3}) = 2.73^{+0.15}_{-0.12}\) which is in an excellent agreement with the mean gas density \(\log(n/\text{cm}^{-3}) \approx 2.5\) of dense neutral/molecular gas found by cosmological zoom-in simulations of prototypical LBGs at \(z \approx 6 - 7\) (Pallottini et al. 2019). Such high density value might also explain the non-detection of the CIII\(\lambda 1907\)Å line (Laporte et al. 2017) in this object.

The best fit burstiness parameter is \(\kappa_s = 3.16^{+1.75}_{-1.39},\) implying that COS-3018 is a moderate starburst galaxy. Note that the presence of an ongoing starburst in COS-3018 has been tentatively suggested by previous studies (Smit et al. 2018) because of the high equivalent-width of optical emission lines \((\text{EW}([\text{O III}]+H\beta)=1424 \pm 43\)Å) (Smit et al. 2015). The \(\kappa_s\) distribution resulting from our analysis shows a double-peak profile, with a lower peak at \(\kappa_s \approx 2\) and the higher one at \(\kappa_s \approx 5.\) We explain this behaviour as follows. There are two possibilities to reproduce the observed \([\text{CII}]/\text{CIII}]\) ratio. The first one corresponds to a low-metallicity solution with \(Z \approx 0.2 Z_\odot\) and \(\kappa_s \approx 5.\) In this case, the \([\text{CII}]\) flux is higher as \(N_{\text{PDR}} \propto Z^{-1}.\) To compen-
sate for the [CII] increase, higher $\kappa_s$, and consequently higher $U$, values are required, resulting in large ionized gas column densities boosting the CII emission (see F19). The second peak at $\kappa_s \approx 2$ corresponds to a higher metallicity ($Z \approx 0.7 Z_\odot$) which produces a thinner PDR region emitting the [CII]. In this situation, in order to fit the observed ratio a lower $\kappa_s$ values is obtained. Note that the plateau at $Z \lesssim 0.2 Z_\odot$ happens because in this regime the [CII] luminosity is independent on $Z$ as $N_{\text{HI}} > N_0$ and hence $N_{\text{PDR}} \approx N_0$ (see F19). In this region of the parameter space, $Z$ is essentially unconstrained. Finally, our MCMC analysis constrains the gas-phase metallicity of COS-3018 in the range $Z = 0.44^{+0.34}_{-0.23} Z_\odot$ that, despite the large scatter due to the above considerations, allows us to safely conclude that COS-3018 is less chemically evolved than the Milky Way along but not extremely metal poor.

Note that while our method simultaneously constrains $\kappa_s$, $Z$ and $n$, in principle one can use the [CII] luminosity alone to estimate the burstiness parameter. Extrapolating the $z \approx 1$ relation $M_g = 30 L_{\text{CII}}/\kappa_s$ (mean absolute deviation of 0.2 dex; Zanella et al. 2018) to the EoR, one finds $\Sigma_g = 30 L_{\text{CII}}/\pi z^2_{\text{CII}} = (7.2 \pm 3.6) \times 10^2 M_\odot$ kpc$^{-2}$. By inverting Eq. 1, we get $\kappa_s = 1.43 \pm 1.0$ which is consistent with $\approx 1\sigma$ with the best fit $\kappa_s$ found with our MCMC.

4 DISCUSSION AND CONCLUSIONS

We have presented a novel method to simultaneously determine the star formation law, gas density and metallicity of galaxies in the EoR. This is done by exploiting the [CII] and CII] surface brightness, and the deviation from the local $\Sigma_{\text{CII]} - \Sigma_{\text{SFR}}$ relation. The method is a MCMC algorithm that allows us to determine the best fit $\kappa_s$, $n$, and $Z$ of a galaxy, and their confidence levels. In particular, we analyzed the case of COS-3018 a LBG at $z = 6.854$, finding that it is a moderate starburst galaxy ($\kappa_s = 3.16^{+1.75}_{-0.60}$), with sub-solar gas-phase metallicity ($Z = 0.44^{+0.23}_{-0.13} Z_\odot$) and a mean gas density of log($n$/cm$^{-3}$) = 2.73$^{+0.15}_{-0.12}$, in very nice agreement with predictions from state-of-the-art simulations of EoR galaxies (Pallottini et al. 2019).

The only other LBG at the end of the EoR for which the KS relation has been constrained is HZ10, for which Pavesi et al. (2019) estimated $\Sigma_g \approx 10^{19} M_\odot$ kpc$^{-2}$ and $\Sigma_c \approx 10^{2} M_\odot$ yr$^{-1}$ kpc$^{-2}$. They also point out that HZ10 has a very low $\kappa_s \approx 0.1$ value, compared to the other LBG in their sample (HZ6) which was undetected in CO. The HZ10/HZ6 CO luminosity ratio is $> 6.5$, in spite of a more modest factor of 3 in their SFR ratio. They proposed that the difference in CO luminosity could be due to: (1) variation in star formation efficiency and/or (2) low-Z/dust abundance suppressing CO emission in HZ6. Our method can help clarifying this point in these and similar EoR systems.

In spite of the success of the method, there are some caveats to keep in mind. The first one is that, by construction, the ISM of the galaxy is approximated with a single gas slab, with an unique density and $Z$. This is obviously a simplification as the [CII] and CIII] emission might not be fully co-spatial. Moreover, different gas phases in the ISM show density variations throughout the galaxy.

Nevertheless, our method offers the first glimpse of global (spatially averaged) properties of EoR galaxies. As essentially no alternative constraints are currently available for EoR sources, our model can provide a first order estimate of their key ISM properties. The obvious advantage is that it can constrain metallicity, mean gas density and - more importantly - the SF law in large samples of sources by using only two emission lines that are detectable by ALMA, current optical/NIR telescopes and, in the near future, JWST.

ACKNOWLEDGEMENTS

LV is supported by a Marie Skłodowska-Curie fellowship (grant agreement No. 746119). AF and SC are supported by the ERC-Adg INTERSTELLAR H2020/740120. AF is partially supported by the C.F. von Siemens-Forschungspreis Alexander von Humboldt-Stiftung Research Award.

REFERENCES

Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Behrens C., Pallottini A., Ferrara A., Gallarani S., Vallini L., 2018, MNRAS, 477, 552
Bigiel F., Leroy A., Walter F., Brinks E., de Blok W. J. G., Madore B., Thornley M. D., 2008, AJ, 136, 2846
Bouwens R. J., et al., 2015, ApJ, 803, 34
Bowler R. A. A., et al., 2014, MNRAS, 440, 2810
Bowler R. A. A., Dunlop J. S., McLure R. J., McLeod D. J., 2017, MNRAS, 466, 3612
Capak P. L., et al., 2015, Nature, 522, 455
Carilli C. L., Walter F., 2013, ARA&A, 51, 105
Carniani S., et al., 2018, MNRAS, p. 1042
Coppin K. E. K., et al., 2007, ApJ, 665, 936
Curtis-Lake E., et al., 2016, MNRAS, 457, 440
D’Odorico V., et al., 2018, ApJ, 863, 129
Daddi E., et al., 2010, ApJ, 714, L118
Dayal P., Ferrara A., 2018, Phys. Rep., 780, 1
De Loose I., et al., 2014, A&A, 568, A62
Dessauges-Zavadsky M., et al., 2015, A&A, 577, A50
Ding J., et al., 2017, ApJ, 838, 122
Felte A., Charlot S., Guzik J., 2016, MNRAS, 456, 3354
Ferland G. J., et al., 2017, Rev. Mex. Astron. Astrophys., 53, 385
Ferrara A., et al., 2019, MNRAS, 489, 1
Foreman-Mackey D., et al., 2013, emcee: The MCMC Hammer, Astrophysics Source Code Library (ascl:1303.092)
Genzel R., et al., 2015, ApJ, 800, 20
Goodman J., Weare J., 2010, CAMCOS, 5, 65
Hashimoto T., et al., 2019, PASJ, 71, 71
Heiderman A., Evans II N. J., Allen L. E., Huard T., Heyer M., 2010, ApJ, 723, 1019
Herrera-Camus R., et al., 2015, ApJ, 800, 1
Hodge J. A., Riechers D., Decarli R., Walter F., Carilli C. L., Daddi E., Dannerbauer H., 2015, ApJ, 798, L18
Hollenbach D. J., Tielens A. G. G. M., 1999, RMP, 71, 173
Hutchison T. A., et al., 2019, ApJ, 879, 70
Jaskot A. E., Ravindranath S., 2016, ApJ, 833, 136
Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., Tanigawa S., 2018, ApJ, 855, 4
Kennicutt R. C. J., 1998, ApJ, 498, 541
Kennicutt R. C., Evans N. J., 2012, ARA&A, 50, 531
Knudsen K. K., Riechers D., Carilli C. L., Jaskot A. E., Kereˇ s D., 2010, ApJ, 723, 1019
Kohandel M., Pallottini A., Ferrara A., Zanella A., Behrens C., Carniani S., Gallarani S., Vallini L., 2019, MNRAS, 487, 3007
Laporte N., Nakajima K., Ellis R. S., Zitrin A., Stark D. P., Mainali R., Roberts-Borsani G. W., 2017, ApJ, 851, 40

MNRA 000, 1–6 (2018)
Mainali R., et al., 2018, MNRAS, 479, 1180
Maioiino R., et al., 2015, MNRAS, 452, 54
Matthee J., et al., 2019, ApJ, 881, 124
Nakajima K., et al., 2018, A&A, 612, A94
Pallottini A., Ferrara A., Gallarani S., Vallini L., Maiolino R., Salvadori S., 2017, MNRAS, 465, 2540
Pallottini A., et al., 2019, MNRAS, 487, 1689
Pavesi R., Riechers D. A., Faisst A. L., Stacey G. J., Capak P. L., 2019, ApJ, 882, 168
Richard J., Kneib J.-P., Ebeling H., Stark D. P., Egami E., Fiedler A. K., 2011, MNRAS, 414, L31
Schmidt M., 1959, ApJ, 129, 243
Schruba A., et al., 2011, AJ, 142, 37
Sharda P., Federrath C., da Cunha E., Swinbank A. M., Dye S., 2018, MNRAS, 477, 4380
Sharda P., et al., 2019, arXiv e-prints, p. arXiv:1906.01173
Shibuya T., Ouchi M., Harikane Y., 2015, ApJS, 219, 15
Smit R., et al., 2015, ApJ, 801, 122
Smit R., et al., 2018, Nature, 553, 178
Stark D. P., et al., 2015, MNRAS, 450, 1846
Stark D. P., et al., 2017, MNRAS, 464, 469
Steidel C. C., Strom A. L., Pettini M., Rudie G. C., Reddy N. A., Trainor R. F., 2016, ApJ, 826, 159
Tacconi L. J., et al., 2013, ApJ, 768, 74
Tilvi V., et al., 2013, ApJ, 768, 56
Vallini L., Gallarani S., Ferrara A., Pallottini A., Yue B., 2015, ApJ, 813, 36
Vallini L., Pallottini A., Ferrara A., Gallarani S., Sobacchi E., Behrens C., 2018, MNRAS, 473, 271
Zanella A., et al., 2018, MNRAS, 481, 1976
de los Reyes M., Kennicutt Robert C. J., 2019, ApJ, 872, 16

This paper has been typeset from a TeX/LaTeX file prepared by the author.