The ALPINE-ALMA [C II] survey: Investigation of 10 galaxies at $z \sim 4.5$ with [O II] and [C II] line emission − ISM properties and [O II]−SFR relation

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ABSTRACT

We present 10 main-sequence *ALPINE* galaxies ($\log (M/M_\odot) = 9.2 - 11.1$ and SFR $= 23 - 190 \, M_\odot \, \mathrm{yr}^{-1}$) at $z \sim 4.5$ with optical [O II] measurements from *Keck*/MOSFIRE spectroscopy and *Subaru*/MOIRCS narrow-band imaging. This is the largest such multiwavelength sample at these redshifts, combining various measurements in the ultraviolet, optical, and far-infrared including [C II]$_{158 \, \mu m}$ line emission and dust continuum from ALMA and Hα emission from *Spitzer* photometry. For the first time, this unique sample allows us to analyse the relation between [O II] and total star-formation rate (SFR) and the interstellar medium (ISM) properties via [O II]/[C II] and [O II]/Hα luminosity ratios at $z \sim 4.5$. The [O II]−SFR relation at $z \sim 4.5$ cannot be described using standard local descriptions, but is consistent with a metal-dependent relation assuming metallicities around 50 per cent solar. To explain the measured dust-corrected luminosity ratios of $\log(L_{\mathrm{[OII]}}/L_{\mathrm{[CII]}}) \sim 0.98^{+0.21}_{-0.22}$ and $\log(L_{\mathrm{[OII]}}/L_{\mathrm{H}\alpha}) \sim -0.22^{+0.13}_{-0.15}$ for our sample, ionization parameters $\log (U) < -2$ and electron densities $\log(n_e/[\mathrm{cm}^{-3}]) \sim 2.5 - 3$ are required. The former is consistent with galaxies at $z \sim 2-3$, however lower than at $z > 6$. The latter may be slightly higher than expected given the galaxies' specific SFR. The analysis of this pilot sample suggests that typical $\log (M/M_\odot) > 9$ galaxies at $z \sim 4.5$ to have broadly similar ISM properties as their descendants at $z \sim 2$ and suggest a strong evolution of ISM properties since the epoch of reionization at $z > 6$.

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

1 INTRODUCTION

Observing and understanding the interstellar medium (ISM) of galaxies is a key to understanding galaxy formation and evolution across cosmic time. Next to the far-infrared providing insights into the abundance of dust and gas, the rest-frame optical emission lines build an important basis to study the ISM. Specifically, these lines are sensitive to the instantaneous star formation, metal content of the gas, hydrogen densities, and ionization rates among a variety of other key parameters.

During the recent years, substantial progress have been made in understanding the ISM properties of galaxies at $z = 2-3$ through large spectroscopic survey such as the *Keck Baryonic Structure Survey* (KBSS; Steidel et al. 2014) or the *MOSFIRE Deep Evolution Field* (MOSDEF) survey (Kriek et al. 2015). Among others, one goal of such surveys is to pinpoint the properties of the ISM via three key parameters: the gas-phase metallicity, the electron density n (in

cm^{-3}), and the dimension-less ionization parameter U.[1] Through simultaneous analysis of multiple optical emission lines, it has been found that these parameters significantly evolve between $z = 2$ and local galaxies, yet there is still some debate on the reasons for this change (Steidel et al. 2014; Masters, Faisst & Capak 2016; Sanders et al. 2016; Strom et al. 2017). The evolution of ISM properties questions the reliability (or validity) of commonly used relations that have been calibrated to local galaxies. One of those is the relation between [O II] emission and star formation rate (SFR) as calibrated to local starburst galaxies (Kennicutt 1998). Similar to Hα, [O II] is related to the current star formation in galaxies. However, as a forbidden line, the excitation of oxygen is sensitive to the abundances and ionization state of the gas and not directly coupled to the ionization radiation of young stars. The relation is therefore expected to change significantly as a function of these properties and hence likely redshift (Kewley, Geller & Jansen 2004).

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[1]The ionization parameter is essentially the ratio of ionizing photon density to hydrogen. It is also a measure for the radiation pressure feedback, as it reflects the radiation-to-gas-pressure ratio (e.g. Yeh & Matzner 2012).

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This motivates the interesting question of how the ISM changes at early cosmic times and whether common local relations are still valid at high redshifts. The latter is important to quantify, as more measurements of optical lines will be provided soon by the *James Webb Space Telescope* (*JWST*). Of specific interest is the redshift range $z = 4-6$. This epoch is fundamental to study the chemical and structural evolution of galaxies as it connects primordial galaxy formation during the epoch of reionization at $z > 6$ with mature galaxy evolution at the peak of cosmic SFR density at $z = 2-3$. A large number of galaxies in this redshift range have been robustly identified via Ly α emission and ultraviolet (UV) absorption lines thanks to large spectroscopic surveys (e.g. Le Fèvre et al. 2015; Hasinger et al. 2018) and are extensively studied in the UV. Unfortunately, current facilities only allow the observation of one strong optical line (the [O II] doublet at rest-frame 3726Å and 3729Å) at these redshifts, thus studies with multiple optical lines as the ones mentioned above are not possible. So far, [O II] has only been observed in 4 galaxies at $z = 4-5$, with three of them lensed (Swinbank et al. 2007, 2009; Troncoso et al. 2014; Shapley et al. 2017). In Shapley et al. (2017), the [O II] as well as the detection of [Ne III]$_{3869}$ has been used to obtain the first direct measurement of the gas-phase metallicity at $z \sim 4.5$ via optical lines. However, further determinations of the ISM properties of these galaxies have not been possible due to the lack of other emission lines.

In this paper, we investigate for the first time the ISM properties of high-z galaxy population via the currently largest sample of 10 typical main-sequence galaxies at $z \sim 4.5$ with optical [O II] emission measurements. We mitigate the lack of optical emission lines by entering the far-infrared and in addition use spectral information from the rest-frame UV. Specifically, we are combining measurements of

(i) rest-UV absorption lines (obtained from *Keck*/DEIMOS spectroscopy).

(ii) optical emission of [O II] (obtained from *Subaru*/MOIRCS narrow-band imaging and *Keck*/MOSFIRE spectroscopy) and H α (obtained from *Spitzer*/IRAC colours), and

(iii) singly ionized Carbon ([C II]$_{158\,\mu m}$ at 158 μm, hereafter denoted as [C II]) and 150 μm dust continuum from ALMA.

The galaxies, located in the *COSMOS* field (Scoville et al. 2007), are all part of the *ALPINE* survey (Béthermin et al. 2020; Faisst et al. 2020a; Le Fèvre et al. 2020), which currently provides the largest multiwavelength post-reionization data set with observations from UV to far-infrared. Thanks to the indirect measurement of metallicity from UV absorption lines as well as additional emission lines such as H α and [C II], we can derive strong constraints on key ISM parameters such as metallicity, electron density, and ionization parameter. Furthermore, the knowledge of the total SFR of the galaxies enables a first calibration of the relation between [O II] and SFR at $z \sim 4.5$.

This paper is organized as follows: In Section 2 we present the spectroscopic and narrow-band observations of [O II], constraints on the metal content from rest-UV absorption lines, and the measurement of H α emission from *Spitzer*. In the following section, we discuss the relation between total SFR and [O II] emission (Section 3.1) and the [O II]/[C II] and [O II]/H α luminosity ratio in the context of the ISM properties of our galaxies (Section 3.2). We conclude in Section 4.

Throughout this work, we assume a ΛCDM cosmology with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.70$, and $\Omega_m = 0.30$. All magnitudes are given in the AB system (Oke 1974) and stellar masses and SFRs are normalized to a Chabrier (2003) initial mass function (IMF) unless noted otherwise.
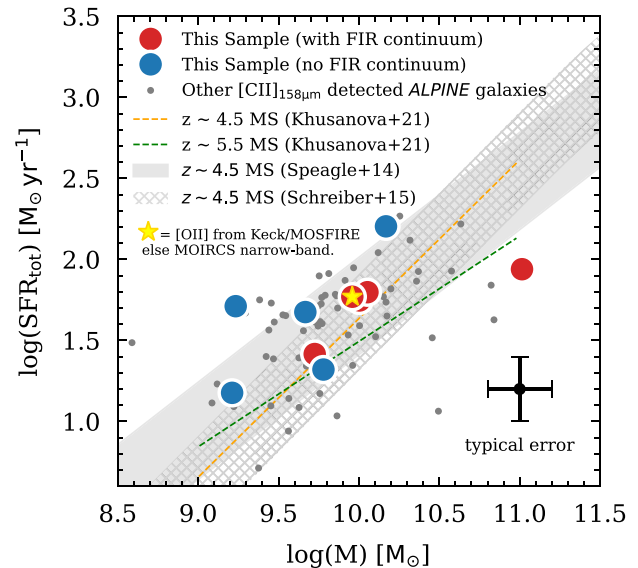
Figure 1. Relation between stellar mass and total SFR for the 10 galaxies with [O II] and [C II] measurements studied in this work (red with far-infrared continuum detection; blue without). The total SFR in this case is computed by the UV+far-infrared continuum (if available) or [C II] alone according to the Schaerer et al. (2020) relation (see Section 3.1.1). *DC_881725*, for which a spectroscopic measurement of [O II] exists, is shown as a yellow star. Other *ALPINE* galaxies with [C II] measurements are shown in grey. We show the main-sequence (MS) parametrizations at $z \sim 4.5$ from Speagle et al. (2014) and Schreiber et al. (2015), the latter extrapolated from *Herschel* observations at $z \sim 3.5$, as well as from *ALPINE* at $z \sim 4.5$ and $z \sim 5.5$ (Khusanova et al. 2020).

2 SAMPLE AND DATA

The 10 galaxies at $z \sim 4.5$ reside in the *Cosmic Evolution Survey* (COSMOS; Scoville et al. 2007) field and are a subset of the *ALPINE* survey (Béthermin et al. 2020; Faisst et al. 2020a; Le Fèvre et al. 2020), which covers in total 118 galaxies in COSMOS and the *Extended Chandra Deep Field South* (ECDFS; Giacconi et al. 2002; Grogin et al. 2011). The galaxies are covered by a wealth of observations at rest-frame UV (obtained by ground-based telescopes and the *Hubble* space telescope), optical (obtained by the *Spitzer* space telescope), and far-infrared (obtained by ALMA) wavelengths. The measurement of the $\sim 150\,\mu m$ dust continuum and [C II] line are detailed in Béthermin et al. (2020). Physical properties including stellar mass, SFR, dust attenuation ($E(B-V)$), and UV continuum slope (β) are derived from the rest-frame UV to optical photometry by using the spectral energy distribution (SED) fitting code LEPHARE (Arnouts et al. 1999; Ilbert et al. 2006). Bruzual & Charlot (2003) composite stellar population models of different ages, metallicities, star-formation histories, and dust attenuation are assumed for the fitting as described in detail in Faisst et al. (2020a). The galaxies are typical galaxies for their cosmic times and lie on the expected $z \sim 4.5$ main-sequence (Fig. 1). The total SFR in this case is computed from the UV and far-infrared continuum or alternatively from the [C II]−SFR relation (Schaerer et al. 2020), which was derived from the IRX−β relation for galaxies without far-infrared continuum detection (Fudamoto et al. 2020). The measurements coincide closely with two parametrizations of the main-sequence at $z \sim 4.5$ from Speagle et al. (2014) and Schreiber et al. (2015). The latter is extrapolated from *Herschel* observations at $z \sim 3.5$.
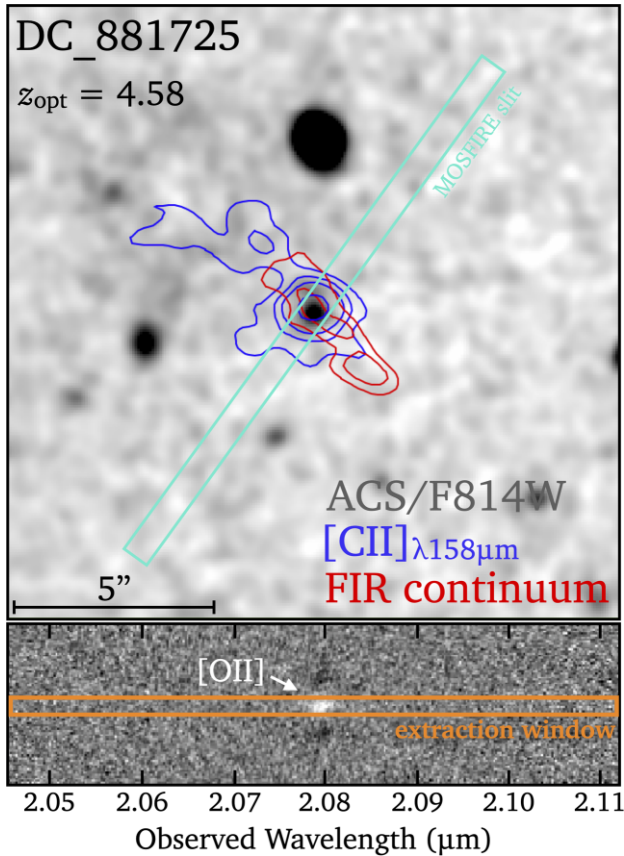
Figure 2. *Keck*/MOSFIRE slit layout on *DC_881725*. Upper panel: ACS/F814W image of *DC_881725* overlaid with contours (1, 3, 5, and 10σ) of far-infrared continuum (red) and [C II] emission (blue) observed by ALMA. The MOSFIRE slit is indicated as the cyan box. The F814W image (Koekemoer et al. 2007) is smoothed by a Gaussian to represent the seeing (FWHM = 0.4 arcsec) during the *Keck* observations. Bottom panel: 2D *Keck*/MOSFIRE spectrum in *K*-band with [O II] emission indicated. The orange box visualizes the extraction window (6 pixels or 1.08 arcsec).

2.1 A unique sample of z ∼ 4.5 galaxies with [O II] measurements

In this study, we present the largest galaxy sample with [O II] measurement at $z \sim 4.5$. For one of the 10 galaxies, we obtain the [O II] measurement from spectroscopy while for the others [O II] is obtained from narrow-band photometry. In the following, we detail the measurements in both cases.

2.1.1 DC_881725: spectroscopic [O II] measurement at z = 4.58

DC_881725 was observed at rest-frame optical wavelengths with the multi-object spectrometer for infrared exploration (*MOSFIRE*; McLean et al. 2010, 2012) on the *Keck* I telescope. This galaxy was originally a filler target part of a *MOSFIRE* program to observe a $z \sim 2.2$ overdensity (PI: Nick Scoville). Hence the galaxy was basically randomly picked from the *ALPINE* sample with the only requirement of having an [O II] flux (estimated from the local SFR versus [O II] relation; Kennicutt 1998) that is bright enough to be detected by the parent observations. The observations cover the optical [O II] doublet at rest-frame wavelengths of 3726 Å and 3729 Å. This is the first main-sequence galaxy at $z \sim 4.5$ with spectroscopic [O II] measurement as well as observations of
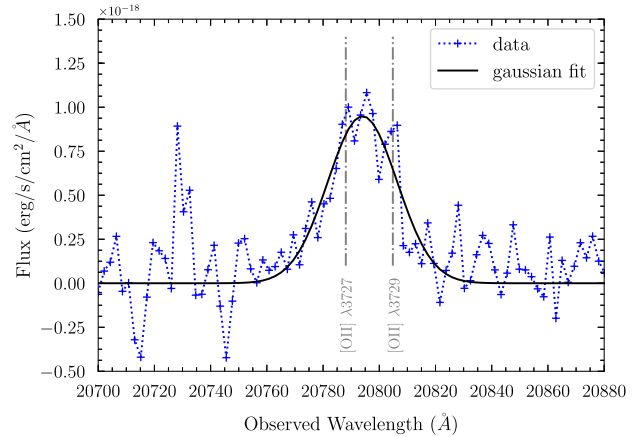

Figure 3. Extracted 1D MOSFIRE spectrum (blue) of *DC_881725* at the location of the [O II] emission line doublet (indicated by the vertical dot-dashed lines). The Gaussian fit (assuming blended lines) is shown in black.

the far-infrared [C II] line emission and continuum at rest-frame 150 μm.

The observations with *MOSFIRE* were carried out on 2019 January 14 in *K*-band (1.93–2.40 μm) under clear sky conditions with an average seeing of 0.4 arcsec and airmass of 1.1–1.2. The galaxy was observed in MCSD mode with 16 reads, ABBA dither pattern, and a slit width of 0.7 arcsec for a total on-target exposure time of 1.2 h (24 × 3 min). The resolution of the spectrum corresponds to $R \sim 3600$, which would allow us theoretically to barely resolve the [O II] doublet if it were at higher signal-to-noise. Fig. 2 shows *DC_881725* in the Hubble ACS/F814W COSMOS mosaics (Koekemoer et al. 2007) (convolved to match the resolution of the ground-based seeing at the time of the *Keck* observations) with the *MOSFIRE* slit overlaid. The far-infrared and [C II] emission observed with ALMA are superimposed as contours. The lower panel shows the 2D spectrum and the window used to extract the 1D spectrum.

The data was reduced and wavelength calibrated using the current MOSFIRE data reduction pipeline.[2] Sky lines were used by the pipeline to perform a wavelength calibration. The absolute flux calibration of the spectrum is detailed in Appendix A. In brief, a magnitude 17 standard star from the 2MASS star catalogue was included in the mask to derive a wavelength-dependent absolute flux calibration of the extracted 1D spectrum.

The 1D spectrum of *DC_881725* is extracted in a spatial window of six pixels (corresponding to 1.08 arcsec at a pixel scale of 0.18 arcsec px^{-1}) around the centre of the identified [O II] emission line. The extracted spectrum in $e^- \, s^{-1}$ is converted to $erg \, s^{-1} \, cm^{-2} \, Å^{-1}$ using the wavelength-dependent normalization described in Appendix A. The extracted spectrum is shown in Fig. 3 (blue dashed line) around the expected location of the [O II] doublet.

The [O II] line flux is derived by fitting a single Gaussian with variable mean, σ, and total flux to the 1D spectrum (Fig. 3, black solid line). We also tried to fit a double Gaussian to account for the doublet nature of the line. However, given the low signal-to-noise and resolution, no robust fit was obtained. The uncertainties of the total flux are determined using 500 Monte Carlo samples for each of which the fluxes are changed according to their uncertainties (assumed Gaussian) obtained from the variance of the spectrum. We

[2] https://keck-datareductionpipelines.github.io/MosfireDRP/

Table 1. Summary of measured properties for *DC_881725* from broad-band photometry, ALMA observations, and new *Keck*/MOSFIRE spectroscopy.

		Broad-band				ALMA		*Keck*/DEIMOS		*Keck*/MOSFIRE	
$\log(M_*)$ $(M_\odot)$	SFR_{SED} $(M_\odot\,yr^{-1})$	$E(B-V)_{SED}$ (mag)	$\log(L_{UV})$ $(L_\odot)$	β	$z_{[CII]}$	$\log(L_{IR})$ $(L_\odot)$	$\log(L_{[CII]})$ $(L_\odot)$	$z_{Ly\alpha}$	$EW(Ly\alpha)$ (Å)	$z_{[OII]}$	$\log(L_{[OIII]})$ $(L_\odot)$
$9.96^{+0.16}_{-0.11}$	$88.0^{+61.1}_{-43.3}$	$0.25^{+0.05}_{-0.05}$	$10.97^{+0.06}_{-0.06}$	$-1.20^{+0.42}_{-0.18}$	4.5777	$11.67^{+0.10}_{-0.13}$	$8.84^{+0.04}_{-0.04}$	4.5854	$57.4^{+18.0}_{-18.0}$	4.5793	$9.22^{+0.05}_{-0.06}$

find a total [O II] line flux of $3.00^{+0.47}_{-0.46} \times 10^{-17}$ erg s^{-1} cm^{-1} Å^{-1} and measure an [O II] redshift of $z_{[O\,ii]} = 4.5793$. The latter matches closely the redshift determined from [C II] ($\sim 123 \pm 30$ km s^{-1} blue-shifted w.r.t. [O II]) but is significantly red-shifted with respect to Ly α by 328 ± 30 km s^{-1}.[3] These quantities as well as the [O II] luminosity, $L_{[O\,ii]}$, are listed in Table 1 along with other properties measured from the ancillary data.

2.1.2 [O II] Measurements from narrow-band imaging

We complement *DC_881725* with nine additional galaxies at $z \sim 4.5$ which have [O II] luminosities derived from narrow-band imaging taken with the Multi-Object Infrared Camera and Spectrograph (MOIRCS; Ichikawa et al. 2006; Suzuki et al. 2008) on the *Subaru* Telescope. The observations were part of the *Charting Cluster Construction with VUDS* (Le Fèvre et al. 2015) and *ORELSE* (Lubin et al. 2009) survey (C3VO; Lemaux et al. 2020; Shen et al. 2021). In brief, the nine *ALPINE* galaxies fall in the footprint of three pointings targeting the massive proto-cluster *PCl J1001+0220* at $z \sim$ 4.57 (Lemaux et al. 2018) and its surrounding in the COSMOS field. Similar to *DC_881725*, they are therefore randomly selected from the *ALPINE* sample but without imposed restrictions on the [O II] flux. The nine galaxies may be part of the proto-cluster structure, however, as shown by studies at lower redshifts (e.g. Darvish et al. 2015), we do not expect significant differences in their properties compared to field galaxies.

The observations were executed between 2020 February 2 and 2021 January 31, using NB2071 (2.043 − 2.097 μm) and NB2083 (2.056 − 2.110 μm) narrow-band filters, under seeing that ranged from ∼0.4−0.8 arcsec and conditions that varied from light cirrus to photometric. The total effective integration time across all three pointings and two filters was approximately 18 h, which was split into 150s individual exposures. A standard circular dither pattern with a set of 10 dithers was adopted.

All raw data were reduced with the IRAF based reduction pipeline MCSRED2 (Tanaka et al. 2011), which performed flat-fielding, masking objects, and sky subtraction. Astrometry calibration was performed by SCAMP (Bertin 2006) for every individual exposure. For each filter and chip, a final narrow-band image was stacked using SWARP (Bertin et al. 2002). The 5σ limiting magnitudes of the images have a median of 23.1 mag and in a range of 22.7 − 23.3 mag, where σ is measured from the flux scatter of randomly distributed 2 arcsec aperture. Note that some exposures were shallower due to the filter wheel occultation. Finally, photometric calibration was performed to the Ks−band image from the UltraVISTA DR4 (McCracken et al. 2012) by selecting a set of bright but unsaturated point sources as the reference stars.

For the source detection and extraction on each narrow-band image, SEXTRACTOR (Bertin & Arnouts 1996) was used in dual-image mode using the much deeper (24.8 mag at 5σ) Ks−band image as the detection image.[4] The point-spread functions (PSFs) of the narrow-band images were degraded to match the Ks-band image. In details, the PSFs for the narrow-band and Ks-image were derived using the PSFEX code (Bertin 2011). Subsequently, the PHOTUTIL package with a Split Cosine Bell window was used to generate a matching kernel between two PSFs. The uncertainties on the fluxes estimated by SEXTRACTOR were scaled to account for correlated pixel noise following the method of Pelliccia et al. (2021).

The following system of two equations involving the narrow-band and the underlying Ks-band photometry was solved for the continuum (f_{cont}^λ) and [O II] line flux (f_{line}^λ) at wavelength λ of the [O II] line (c.f. Hu et al. 2019):

$$\bar{f}_{NB/Ks}^\lambda = \frac{\int \left(f_{line}^\lambda + f_{cont}^\lambda\right) T_{NB/Ks}^\lambda d\lambda}{\int T_{NB/Ks}^\lambda d\lambda}. \tag{1}$$

In the above equation, $\bar{f}_{NB}^\lambda$ and $\bar{f}_{Ks}^\lambda$ denote the detected flux densities in each narrow-band and the Ks-band, and T_{NB}^λ and T_{Ks}^λ are the corresponding filter transmission functions. In the calculation, we assumed an [O II] line profile resembling a δ-function in each narrow-band filter and a flat continuum profile. As the observed line width of the [O II] doublet ($29.01^{+5.33}_{-4.64}$ Å, see Fig. 3) is much narrower than the width of the narrow-band filter (~ 270 Å), so the [O II] line profile does not affect the result of this calculation. The uncertainties of the [O II] fluxes were obtained using Monte Carlo iterations for each of which the narrow-band and Ks-band fluxes were drawn from a Gaussian distribution with a width corresponding to their associated uncertainties. The [O II] flux uncertainty is then defined as the 16th and 84th quantiles of the resulting [O II] flux distribution. Finally, an inverse-variance weighting scheme was adopted to combine fluxes obtained from the two narrow-band filters, with weights defined as $W_i = T_i^2/\sigma_i^2$, where T_i is the narrow-band transmission curve at the [C II] redshift and σ_i is the narrow-band flux uncertainty.

Table 2 lists the measured [O II] luminosities as well as other properties derived from the ancillary data for these nine galaxies.

2.2 Estimate of metal-enrichment from rest-frame UV absorption lines

Commonly, the gas-phase metal content of galaxies is measured by flux ratios of bright optical lines such as [O II], [O III], and H α (e.g. Pettini & Pagel 2004; Maiolino & Mannucci 2019). Recently, thanks to ALMA, also far-infrared emission lines such as [N II]$_{205\,\mu m}$, [O II]$_{88\,\mu m}$, and [C II] are used to estimate the gas-phase metal content of high-redshift galaxies (e.g. Croxall et al. 2017; Pavesi et al. 2019; Jones et al. 2020; Yang & Lidz 2020; Vallini et al. 2021). The former are not accessible at these redshifts currently (except [O II]), while

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[3] The velocity shifts quoted assume equal flux of the two blended [O II] lines. We estimate an uncertainty of ± 30 km s^{-1} assuming [O II]$_{\lambda 3729}$/[O II]$_{\lambda 3726}$ ratios between 0.35 and 1.5, corresponding to the high and low electron density regime (Osterbrock 1974).

[4] We set detection parameters of DETECT_MINAREA =5, DE-TECT_THRESH =1.5, and ANALYSIS_THRESH =1.5. The latter two are relative (σ) thresholds.

Table 2. Summary of properties derived from the ancillary data for the nine galaxies with [O II] detection from narrow-band imaging.

ID	$z_{[CII]}$	$\log(L_{OII})$ $(L_\odot)$	$\log(L_{[CII]})$ $(L_\odot)$	$\log(L_{FIR})$ $(L_\odot)$	$\log(M)$ $(M_\odot)$	$SFR_{[CII]}$ $(M_\odot\ yr^{-1})$	SFR_{FIR} $(M_\odot\ yr^{-1})$	SFR_{UV} $(M_\odot\ yr^{-1})$
DC_665626	4.5830	$9.36^{+0.08}_{-0.09}$	$8.21^{+0.10}_{-0.13}$	–	$9.21^{+0.16}_{-0.18}$	$23.15^{+1.22}_{-1.30}$	–	$5.77^{+1.24}_{-1.23}$
DC_680104	4.5320	$9.51^{+0.10}_{-0.13}$	$8.74^{+0.12}_{-0.16}$	–	$9.23^{+0.14}_{-0.12}$	$66.30^{+1.25}_{-1.36}$	–	$14.55^{+1.12}_{-1.10}$
VC_5100969402	4.5869	$9.34^{+0.08}_{-0.10}$	$8.72^{+0.04}_{-0.05}$	$11.65^{+0.11}_{-0.16}$	$10.00^{+0.14}_{-0.12}$	$63.42^{+1.09}_{-1.10}$	$43.23^{+13.06}_{-13.06}$	$12.50^{+1.14}_{-1.13}$
VC_5100994794	4.5783	$9.14^{+0.11}_{-0.15}$	$8.75^{+0.04}_{-0.04}$	$11.20^{+0.12}_{-0.16}$	$9.73^{+0.13}_{-0.09}$	$66.93^{+1.08}_{-1.15}$	$15.50^{+4.71}_{-4.71}$	$10.69^{+1.19}_{-1.23}$
VC_5101209780	4.5700	$8.99^{+0.30}_{-0.38}$	$8.86^{+0.08}_{-0.10}$	$11.62^{+0.13}_{-0.19}$	$10.05^{+0.12}_{-0.12}$	$84.45^{+1.18}_{-1.23}$	$40.65^{+14.64}_{-14.64}$	$22.07^{+1.09}_{-1.10}$
VC_5101210235	4.5733	$9.06^{+0.16}_{-0.30}$	$8.35^{+0.11}_{-0.14}$	–	$9.78^{+0.15}_{-0.12}$	$30.71^{+1.24}_{-1.33}$	–	$24.08^{+1.08}_{-1.07}$
VC_5101218326	4.5678	$9.32^{+0.08}_{-0.10}$	$9.26^{+0.02}_{-0.02}$	$11.79^{+0.07}_{-0.08}$	$11.01^{+0.05}_{-0.07}$	$184.45^{+1.04}_{-1.04}$	$60.38^{+10.30}_{-10.30}$	$27.94^{+1.06}_{-1.07}$
VC_5101244930	4.5769	$9.09^{+0.30}_{-0.19}$	$8.70^{+0.08}_{-0.10}$	–	$9.67^{+0.05}_{-0.16}$	$61.73^{+1.18}_{-1.23}$	–	$17.45^{+1.12}_{-1.12}$
VC_5110377875	4.5441	$9.21^{+0.18}_{-0.32}$	$9.23^{+0.03}_{-0.03}$	–	$10.17^{+0.21}_{-0.12}$	$174.87^{+1.05}_{-1.06}$	–	$24.67^{+1.09}_{-1.08}$

Note. The UV SFRs have not been corrected for dust attenuation. [C II] SFRs derived using the Schaerer et al. (2020) relation (see Section 3.1.1). Far-infrared SFRs derived using the Kennicutt (1998) relation.

the latter are not available for our galaxies as their observations are costly (except [C II]) or only possible for galaxies at $z > 6$ (in the case of $[O\ II]_{88\ \mu m}$).

None the less, we can estimate the metal content of our galaxies from the exquisite rest-frame UV spectra in an indirect way. Specifically, the strength, i.e. equivalent-width (EW; note that EWs of absorption lines are defined positive), of rest-frame UV absorption lines correlates with metal content (e.g. Leitherer et al. 2011). This correlation has different origins including the evolutionary stage of stellar populations, metal-dependent winds impacting the width of absorption lines, or dust extinction. The technique has already been applied to similar main-sequence galaxies at $z \sim$ 4–6 (Ando et al. 2007; Faisst et al. 2016b) and has been tested empirically at lower redshifts (Faisst et al. 2016b). The S/N of individual rest-UV spectra of our galaxies is too low to estimate their metal content. We therefore perform median stacking the 10 spectra before we compute the EWs of several absorption complexes around Si III (~ 1300 Å), C II (~ 1335 Å), Si IV (~ 1400 Å), and C IV (~ 1550 Å). The uncertainties are computed via Monte Carlo iterations including the spectral variances. We then use the relations between absorption line EW and metallicity as calibrated via galaxies in the local Universe as well as $z \sim 2$ and $z \sim 3$ in Faisst et al. (2016b).

The stacked spectrum and the results from this analysis are shown in Fig. 4. The blue horizontal swaths show the measured EWs of each absorption complex with uncertainty and the grey swaths show the calibration derived in Faisst et al. (2016b). Looking at the individual absorption complexes suggests average metallicites between 10 per cent and 50 per cent of solar, except for Si III, which is consistent with solar metallicity. We note that even for the stack the S/N is relatively low, which is likely the cause for the apparent differences between the individual absorption complexes. Combining the probability distribution functions of all absorption complexes, we find an average metallicity of $12 + \log (O/H) = 8.41^{+0.31}_{-0.54}$. This corresponds to roughly ~ 50 per cent of the solar metallicity.[5] Such values are consistent with the expected metallicity based on the stellar masses of our galaxies at these redshifts (Ando et al. 2007; Faisst et al. 2016b).

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[5]We assume a solar oxygen abundance of $\log(O/H) + 12 = 8.76$ according to the 'galactic concordance abundances' (Nieva & Przybilla 2012; Nicholls et al. 2017), which is close to the primordial solar abundance (Asplund et al. 2009).
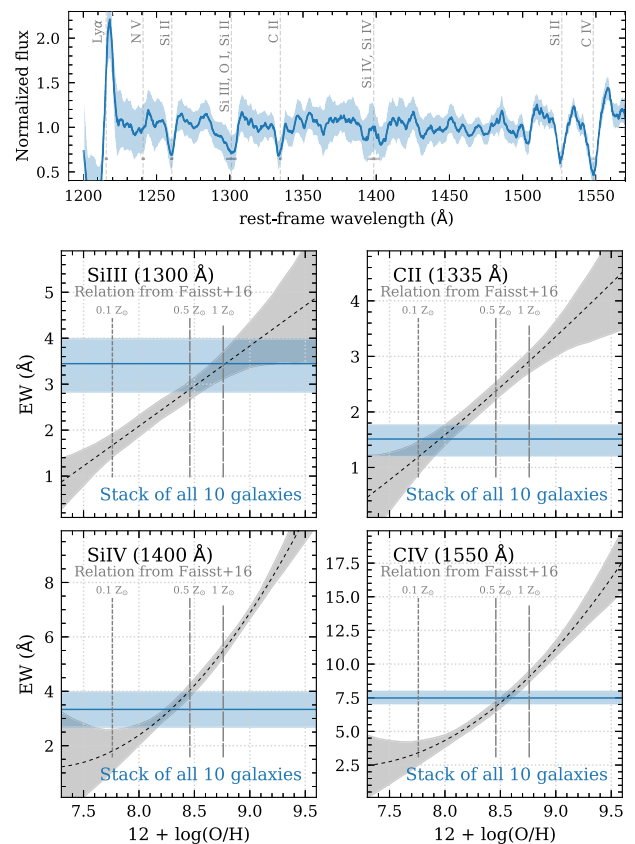

Figure 4. Top panel: Flux-normalized stacked UV spectrum of the 10 galaxies studied in this work. Prominent spectral features are indicated. The light area shows the 1σ scatter determined from individual variances of the spectra. Bottom panels: The EWs of rest-frame UV absorption lines provide an indirect measure of the metal content. The blue swaths show the measured EWs of each absorption complex from a stack of all 10 galaxies in our sample. The grey swath shows the calibration between EW and metallicity from Faisst et al. (2016b). The vertical dashed lines mark 0.1, 0.5, and 1 $Z_\odot$.

2.3 Photometric measurement of H α from *Spitzer*

The coverage of our galaxies by *Spitzer* allows us to photometrically estimate their H α emissions via the $[3.6\ \mu m] − [4.5\ \mu m]$ colours. This method has been successfully used by several studies very early on (e.g. Shim et al. 2011; Stark et al. 2013; Mármol-Queraltó

et al. 2016; Rasappu et al. 2016) and it is shown to result in photometric Hα measurements that are statistically consistent with spectroscopy (e.g. Faisst et al. 2016a). The detailed derivation of this measurement for the *ALPINE* galaxies is described in Faisst et al. (2020a). The luminosities are corrected for dust in the same way as [O II]. As an additional check, we compare our Hα measurement to the *EL-COSMOS* catalogue (Saito et al. 2020), which contains Hα emission line predictions from SED fitting for all galaxies from the Laigle et al. (2016) COSMOS catalogue. We find good agreement within a factor of 2–5 (see Appendix B). We find a similar agreement when comparing the [O II] luminosities provided in the *EL-COSMOS* catalogue to our spectroscopic and narrow-band imaging measurements, which verifies the reliability of the catalogue.

3 DISCUSSION

3.1 The [O II]−SFR relation at $z \sim 4.5$

We first investigate whether the local relation between [O II] emission and total star formation is still valid at $z \sim 4.5$. For this we make use of our multiwavelength measurements of the total SFR from UV and far-infrared data.

3.1.1 Total SFRs derived from UV+far-infrared continuum and [C II] emission

In order to relate [O II] emission to total star formation, we have to provide measurements of the latter that are as robust as possible. Our sample allows us to do this via the combination of measurement of UV and far-infrared continuum as well as [C II] emission.

For galaxies detected in far-infrared continuum (5 out of 10), we compute the total SFR as the sum of UV and dust obscured star formation. Specifically, we make use of the relations detailed in Kennicutt (1998) (see also Kennicutt & De Los Reyes 2021),

$$\text{SFR}_{\text{UV}} \left(M_\odot \, \text{yr}^{-1} \right) = 0.79 \times 10^{-28} L_\nu \left(\text{erg s}^{-1} \, \text{Hz}^{-1} \right) \tag{2}$$

and

$$\text{SFR}_{\text{IR}} \left(M_\odot \, \text{yr}^{-1} \right) = 2.54 \times 10^{-44} L_{\text{IR}} \left(\text{erg s}^{-1} \right). \tag{3}$$

These SFR values have already been converted from a Salpeter (1955) to a Chabrier (2003) IMF by division of a factor of 1.77 (in linear scale). For details on the derivation of the UV and far-infrared luminosity we refer to Faisst et al. (2020a) and Béthermin et al. (2020), respectively. Note that the derivation of L_{IR} depends strongly on the shape of the far-infrared SED, with specifically the dust temperature playing an important role (e.g. Faisst et al. 2017). Here, we make use of the stacked far-infrared SED derived from Herschel, SCUBA, and ALMA photometry of $z = 4$–6 galaxies in COSMOS with similar SFR and stellar masses as the *ALPINE* galaxies (see Béthermin et al. 2020). The dust temperature of this stack is 43 ± 5 K, which is consistent with the individual dust temperatures measured for 4 *ALPINE* galaxies with sufficient far-infrared coverage from ALMA (Faisst et al. 2020b).

For the remaining five galaxies without far-infrared continuum detection, we use the relation between [C II] line emission and total SFR as presented by Schaerer et al. (2020),

$$\log \left(\text{SFR}_{\text{[CII]}} / \left[M_\odot \, \text{yr}^{-1} \right] \right) = \frac{\log(L_{\text{[CII]}}/L_\odot) - 6.61}{1.17}. \tag{4}$$

The above relation is based on total SFRs of all *ALPINE* galaxies (with limits from [C II] non-detection properly taken into account). For galaxies without far-infrared detection, the IRX−β relation

Table 3. Summary of SFRs measured from [O II] and ancillary *ALPINE* data available for *DC_881725*. Note that SFRs from UV and optical indicators have not been corrected for dust attenuation.

Reference	SFR (M$_\odot$ yr^{-1})			
	[O II]	[C II]	IR	UV
K98	$50.0^{+6.7}_{-6.1}$	–	$46.0^{+11.9}_{-11.9}$	$13.3^{+2.0}_{-1.8}$
K04[†]	–	–	–	–
- no met. dep.	$23.6^{+3.2}_{-2.7}$	–	–	–
- solar	$18.6^{+2.5}_{-2.3}$	–	–	–
- half-solar	$13.8^{+1.9}_{-1.7}$	–	–	–
- 1/5$^{\text{th}}$-solar	$10.3^{+1.4}_{-1.5}$	–	–	–
L14				
- metal-poor dwarfs	–	$22.0^{+1.6}_{-1.6}$	–	–
- starburst	–	$59.9^{+5.5}_{-5.5}$	–	–
- AGN	–	$73.0^{+6.0}_{-6.1}$	–	–
- high-z	–	$80.9^{+8.9}_{-8.7}$	–	–
- ULIRGs	–	$360.7^{+4.3}_{-4.3}$	–	–
S20	–	$64.1^{+6.2}_{-5.7}$	–	–
dust correction factor[‡]	5.2 (4.3)	–	–	3.4 (3.5)

Notes. [†] The first value is derived using their equation (4). The other values are derived for different gas-phase metallicities and their equation (10).
[‡] Dust correction factor for [O II] and UV continuum emission assuming a reddening curve from Calzetti et al. (2000) and Reddy et al. (2015) (in parenthesis), respectively (see the text for more details). The [O II] correction factor assumes a differential dust attenuation $f = 0.44$. For $f = 0.7$, decrease the value by a factor of 1.8.
References: K98 − Kennicutt (1998); K04 − Kewley et al. (2004); L14 − De Looze et al. (2014); S20 − Schaerer et al. (2020).

(Fudamoto et al. 2020) is used to derive their far-infrared luminosities and total SFRs.

The total SFR for the nine narrow-band detected galaxies are listed in Table 2. The total SFRs of *DC_881725* derived from UV and far-infrared as well as [C II] for comparison are listed in Table 3. Note that the [C II] and far-infrared (if available) derived SFRs are very comparable as the former have been calibrated by the latter in Schaerer et al. (2020).

We can also compare different [C II]−SFR relations derived in De Looze et al. (2014) with our total SFRs derived for the five galaxies with far-infrared continuum detection. These relations have been calibrated using low-metallicity dwarfs ($12 + \log(\text{O/H}) \sim 7.1$–8.4), starbursts (and H II regions), galaxies with an active galactic nucleus (AGN), ultra-luminous infrared galaxies (ULIRGs), and high-redshift galaxies (mostly at $z \sim 1$–3). We find that (i) the [C II]−SFR relation of local metal-poor dwarfs underestimates the total SFR by 0.43 ± 0.13 dex, while (ii) the relation derived from ULIRGs overestimates the total SFRs by 0.77 ± 0.15 dex. The other calibrations are roughly consistent with our derived values within 1σ uncertainties. Similar results are found for the remaining five galaxies with SFRs derived from [C II] using the Schaerer et al. (2020) relation. This SFR comparison suggests that our galaxies are not comparable to either local low-metallicity dwarfs or local ULIRGs. This is not surprising as rest-frame UV absorption line spectroscopy suggests that our galaxies are rather metal enriched (see Section 2.2). Furthermore, their far-infrared luminosities are about an order of magnitude lower than those of local ULIRGs included in De Looze et al. (2014) ($L_{\text{IR}} \sim 3 \times 10^{12}$ L$_\odot$). Table 3 shows a detailed list of SFRs derived by the different [C II]−SFR relations for the example of *DC_881725*.
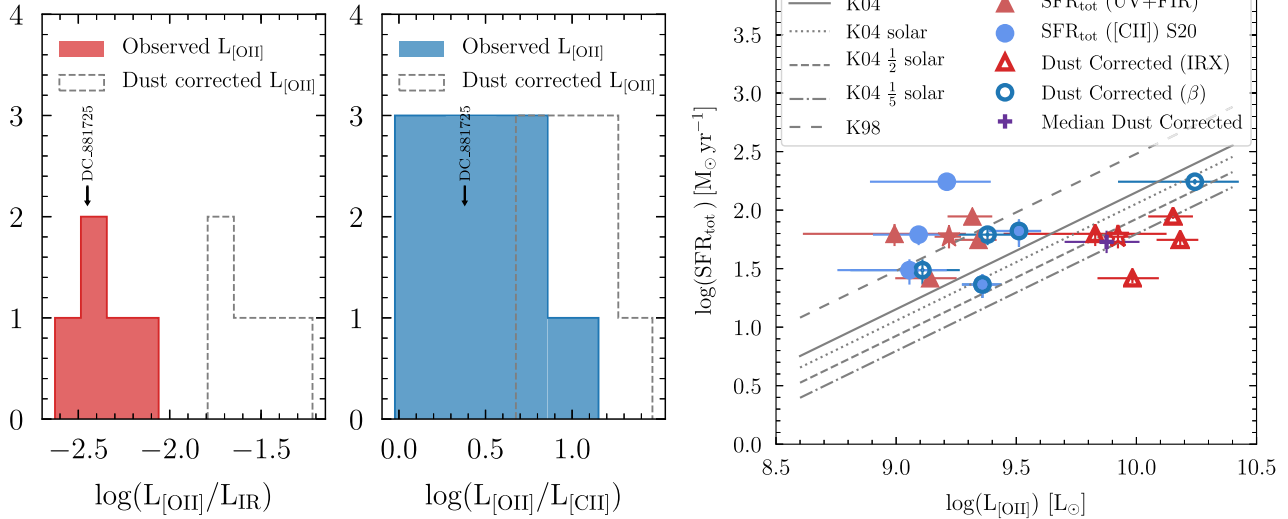
Figure 5. Left-hand panels: Histograms of the L_{OII}/L_{IR} (left) and L_{OII}/L_{CII} (right) ratios for the 10 galaxies. The observed ratios for *DC_881725* are indicated with arrows. The filled histograms show observed ratios (not corrected for dust) and the dashed histograms show dust-corrected ratios (see the text for details). Right-hand panel: Relation between [O II] emission and total SFR. The red (blue) symbols show galaxies with (without) far-infrared detections from ALMA. In the former case, the total SFR is SFR_{UV+IR}; in the latter case, the total SFR is derived from [C II] emission. The filled lighter symbols show observed [O II] luminosities (not corrected for dust) while the empty darker symbols show dust corrected [O II] luminosities. For far-infrared detected galaxies, the dust correction is derived from the IRX value directly. For the others, the relation between β and IRX is used (see Section 3.1.2). Note that some galaxies have little dust, in which cases the filled and empty symbols coincide. *DC_881725* is shown as star. The purple 'plus' denotes the median dust corrected [O II] luminosity. We also show different empirical [O II]−SFR relations from Kennicutt (1998, long dashed line) and the updated version from Kewley et al. (2004, solid line), as well as the metallicity-dependent models from Kewley et al. (2004, dotted, short dashed, and dot-dashed lines for solar, 50 per cent solar, and 20 per cent solar metallicity).

3.1.2 The [O II]−SFR relation at z ∼ 4.5

With measured robust total SFRs for our galaxies, we can now relate these values to the [O II] emission.

The left-hand panels of Fig. 5 show the histograms of the L_{OII}/L_{IR} and L_{OII}/L_{CII} luminosity ratios. We find observed median ratios of $\log(L_{[OII]}/L_{[CII]}) = 0.39^{+0.35}_{-0.32}$ and $\log(L_{[OII]}/L_{IR}) = -2.45^{+0.23}_{-0.09}$. The corresponding dust-corrected ratios are $\log(L_{[OII]}/L_{[CII]}) = 0.98^{+0.21}_{-0.22}$ and $\log(L_{[OII]}/L_{IR}) = -1.64^{+0.23}_{-0.13}$, respectively.

With [O II] being an optical line, it has to be corrected for the effect of dust attenuation. We compute [O II] dust correction factors using the stellar continuum dust attenuation $E_s(B-V)$ values via

$$f_{corr} = 10^{0.4E_s(B-V)k_\lambda/f}, \tag{5}$$

where k_λ is the reddening curve with $\lambda = 3727\,Å$ and we assume a differential dust attenuation factor between stellar continuum and nebular emission of $f = 0.44$ (Calzetti et al. 2000).[6] The $E_s(B-V)$ values are estimated by the following procedure. For galaxies that are detected in far-infrared continuum, we used their IRX ratio ($\equiv \log(L_{IR}/L_{UV})$) to estimate the dust attenuation at rest-frame 1600 Å (A_{1600}) via the relation given in Hao et al. (2011),[7]

$$A_{1600} = 2.5\log\left(1 + 0.46 \times 10^{IRX}\right). \tag{6}$$

The nebular $E(B-V)$ values, $E_n(B-V)$, are then estimated using the relation $A_{1600} = 4.39 \times E_n(B-V)$ (Calzetti et al. 2000). Other parametrizations (e.g. Reddy et al. 2015) lead to values that are different by less than 20 per cent. For galaxies that are not detected in far-infrared continuum, we derive the stellar $E_s(B-V)$ values from the UV continuum photometry. Specifically, we explore the values from SED fitting directly as well as derived from the UV continuum slope (β) using the dust parametrizations by Calzetti et al. (2000) and Reddy et al. (2015). As an additional comparison, we also derive IRX values directly from the β slopes using the IRX−β relation fit for *ALPINE* galaxies at $z \sim 4.5$ in Fudamoto et al. (2020). We find that all four methods agree within 0.05 mag, which results in < 30 per cent differences in the dust factors for [O II]. All in all, we find [O II] dust attenuation factors (linear) between 1 and 5, except in one case where we find a value of $f_{corr} \sim 10$. The different k_λ parametrizations used above result in variations of < 40 per cent (leading to uncertainties of < 0.14 dex in [O II] luminosity). The differential dust attenuation between nebular emission and stellar continuum is by far the largest contribution to the total uncertainty. There is observational evidence that the f−factor of $z > 2$ galaxies is closer to 0.7 than the locally measured value of 0.44 (Kashino et al. 2017; Faisst et al. 2019; Rodriguez-Munoz et al. 2022). In the case of $f = 0.7$, the dust attenuation factors would decrease by a factor of 1.5 (0.18 dex change in luminosity) on average for our sample.

Finally, the right-hand panel of Fig. 5 relates the observed (solid symbols) and intrinsic (dust-corrected, empty symbols) [O II] luminosities to the total star formation (as described in Section 3.1.1). The far-infrared detected galaxies (dust correction from the IRX ratio) are shown as triangles, the remaining galaxies are shown as circles. *DC_881725* is denoted with a star and the median of the dust-corrected [O II] luminosity and total SFR is marked as a purple

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[6]The 'f−factor' is the differential dust attenuation between nebular emission and stellar continuum and is defined as $f = E_s(B-V)/E_n(B-V)$.

[7]Note that this parametrization is consistent with earlier derivations (e.g. from Meurer, Heckman & Calzetti 1999; Kong et al. 2004; Buat et al. 2005; Burgarella, Buat & Iglesias-Páramo 2005).

cross. The measurement uncertainties in [O II] luminosities are large compared to the measurement uncertainties in total SFR (on the order of 0.1 dex). However, we expect systematic errors in the total SFRs to be a factor of $2-3$ larger given the uncertainties in the relation between [C II] and SFR.

Along with our data, we show different parametrizations of the [O II]$-$SFR relation from the literature. We include the original relation by Kennicutt (1998),[8]

$$\text{SFR}^{\text{K98}}_{[\text{O\,ii}]}\left(\text{M}_\odot\,\text{yr}^{-1}\right) = (0.79 \pm 0.23) \times 10^{-41} L_{[\text{OII}]}\left(\text{erg s}^{-1}\right), \quad (7)$$

as well as an updated version provided by equation (4) in Kewley et al. (2004)[9]

$$\text{SFR}^{\text{K04}}_{[\text{O\,ii}]}\left(\text{M}_\odot\,\text{yr}^{-1}\right) = (3.72 \pm 0.93) \times 10^{-42} L_{[\text{OII}]}\left(\text{erg s}^{-1}\right). \quad (8)$$

As pointed out by these authors, this relation may depend significantly on the gas-phase metallicity of the galaxies. We therefore also show their theoretical relations for solar, half-solar, and one-fifth solar metallicity obtained by equation (10) in Kewley et al. (2004)[10]

$$\text{SFR}^{\text{K04}}_{[\text{O\,ii}]}(Z)\left(\text{M}_\odot\,\text{yr}^{-1}\right) = \frac{4.46 \times 10^{-42} L_{[\text{OII}]}\left(\text{erg s}^{-1}\right)}{(-1.75 \pm 0.25)[\log(\text{O/H}) + 12] + (16.73 \pm 2.23)}. \quad (9)$$

We find that the original Kennicutt (1998) relation would significantly overestimate [O II]-derived SFRs by factors of 3–5 if applied to *dust-corrected* [O II] luminosities. Note that the relation in equation (7) required dust corrections of [O II] at the Hα rest-frame wavelength (see description in Kennicutt 1998). However, at the dust attenuation values of our galaxies, this would reduce the dust correction factors by less than 40 per cent (and similarly the overestimation), hence cannot account for the discrepancy. A much better estimate of the total SFR is provided by the updated and metal-dependent [O II]$-$SFR relations by Kewley et al. (2004) (detailed numbers for the case of *DC_881725* are listed in Table 3). The large uncertainties, mainly due to the unknown differential dust attenuation factors but also the uncertain total SFR, do not allow us to distinguish relations for different metallicities at significance. As shown by the purple cross denoting the median value of the dust-corrected [O II] luminosities and total SFRs, subsolar metallicities are the most likely choice but solar metallicites cannot be excluded given the combination of measurement and systematic uncertainties. Also, note that an increase of the $f-$factor from local 0.44 to $\sim$0.7 would reduce the dust correction for the [O II] luminosity by < 0.2 dex (see above), which would keep our observations consistent with the (Kewley et al. 2004) relation at subsolar metallicity.

3.2 Constraints on ISM properties from CLOUDY analysis

In this section, we compare the $\log(L_{[\text{O\,ii}]}/L_{[\text{C\,ii}]})$ and $\log(L_{[\text{O\,ii}]}/L_{\text{H}\alpha})$ luminosity ratios from measurements presented in Sections 2.1 and 2.3 to theoretical values obtained by CLOUDY (C17.02; Ferland et al. 2017) to study key parameters of the ISM of our galaxies.

For the CLOUDY simulation, we assume gas with plain-parallel geometry including Orion-type grains as well as Polycyclic Aromatic Hydrocarbons (PAHs). We ran models for gas clouds with electron densities of $\log(n_{\text{H}}/\text{cm}^{-3}) = [0.5, 2]$, gas-phase metallicities of $Z = [0.1, 0.5, 1.0]\,Z_\odot$, and ionization parameters between $-3.0 < \log(U) < -0.5$ in steps of 0.5 dex. The stopping criteria of the simulation is crucial, especially for computing the [C II] emission,

which can originate from low-density warm ISM. We use a stopping point at $A_{\text{v}} = 100$ mag and we found that lower values such as $A_{\text{v}} = 10$ mag do not have a significant impact on our results. We also investigated the dependence of our results on different star formation histories for the underlying stellar population. For this, we assumed three different simple models: (A) a starburst with an age of 100 Myr; (B) a constant star formation history; (C) the best-fitting SED of *DC_881725*. The first two are produced by the BPASS v2.0 models (Eldridge et al. 2017; Stanway & Eldridge 2018), assume 10 per cent solar stellar metallicity, and include binary-star evolution. The latter is derived from broad-band photometry using CIGALE (Burgarella et al. 2005; Noll et al. 2009; Boquien et al. 2019). The results are shown in Fig. 6. The panel labels indicate the assumption of the underlying stellar population (*A*, *B*, or *C*, respectively). The left-hand and right-hand columns show the result for $\log(L_{[\text{O\,ii}]}/L_{\text{H}\alpha})$ and $\log(L_{[\text{O\,ii}]}/L_{[\text{C\,ii}]})$, respectively. In the following, we compare the models to the observations in more detail.

3.2.1 The $\log(L_{[O\,II]}/L_{H\alpha})$ luminosity ratio

Let us first have a look at the $\log(L_{[\text{O\,ii}]}/L_{\text{H}\alpha})$ luminosity ratio. As seen on the left-hand panels in Fig. 6, this ratio shows a strong negative correlation with the ionization parameter (radiation pressure) U, however is largely independent of the electron density and the changes with metallicity are small compared to the accuracy of our observations. Thus the $\log(L_{[\text{O\,ii}]}/L_{\text{H}\alpha})$ luminosity ratio allows us to put constraints on the ionization parameter U. The trends are slightly flatter for a constant star formation history or using the best-fitting SED. However, overall the impact of the three different star formation histories is negligible at the current accuracy of our measurements.

The observed median dust-corrected $\log(L_{[\text{O\,ii}]}/L_{\text{H}\alpha})$ ratio $(-0.22^{+0.13}_{-0.15})$ and population scatter is indicated as black line with grey area, respectively. Note that we are only using 7 out of the 10 galaxies whose *Spitzer* photometry is not contaminated by nearby sources. *Spitzer*-derived Hα luminosities are mainly uncertain because of the unknown dust correction (specifically the unknown $f$$-$factor). However, the [O II] to Hα luminosity ratio is expected to be rather stable as the [O II] and Hα lines are affected by dust in a similar way (and have likely similar $f-$factors). For example, a change in f from 0.44 to 0.7 affects the luminosity ratio by less than 0.1 dex, which is smaller than sample scatter and measurement uncertainties. Different reddening curves contribute even less to the uncertainties.

Comparing our observations to the CLOUDY models, we find that low ionization parameters ($\log(U) < -2$ or $\log(q/\text{cm\,s}^{-1}) < 8.5$)[11] are favoured independent of the assumed electron density and metallicity. Such ionization parameter values are very consistent with typical measurements at $z = 2$–3 (via the [O III]/[O II] line ratio) finding $\log(U) \sim -2.5$ or $\log(q/\text{cm\,s}^{-1}) \sim 8$ (Nakajima & Ouchi 2014; Sanders et al. 2016, 2020). On the other hand, studies at $z > 6$ suggest $\log(U) \sim -1.7$, which would indicate an increase in ionization parameter in the epoch of reionization (Stark et al. 2014, 2015; Hutchison et al. 2019; Harikane et al. 2020). Note that observations of local H II regions suggest an upper cut-off due to radiation confinement of $\log(U) \sim -1$ (e.g. Yeh & Matzner 2012).

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[8]Converted to a Chabrier (2003) IMF.

[9]Converted to a Chabrier (2003) IMF.

[10]Converted to a Chabrier (2003) IMF.

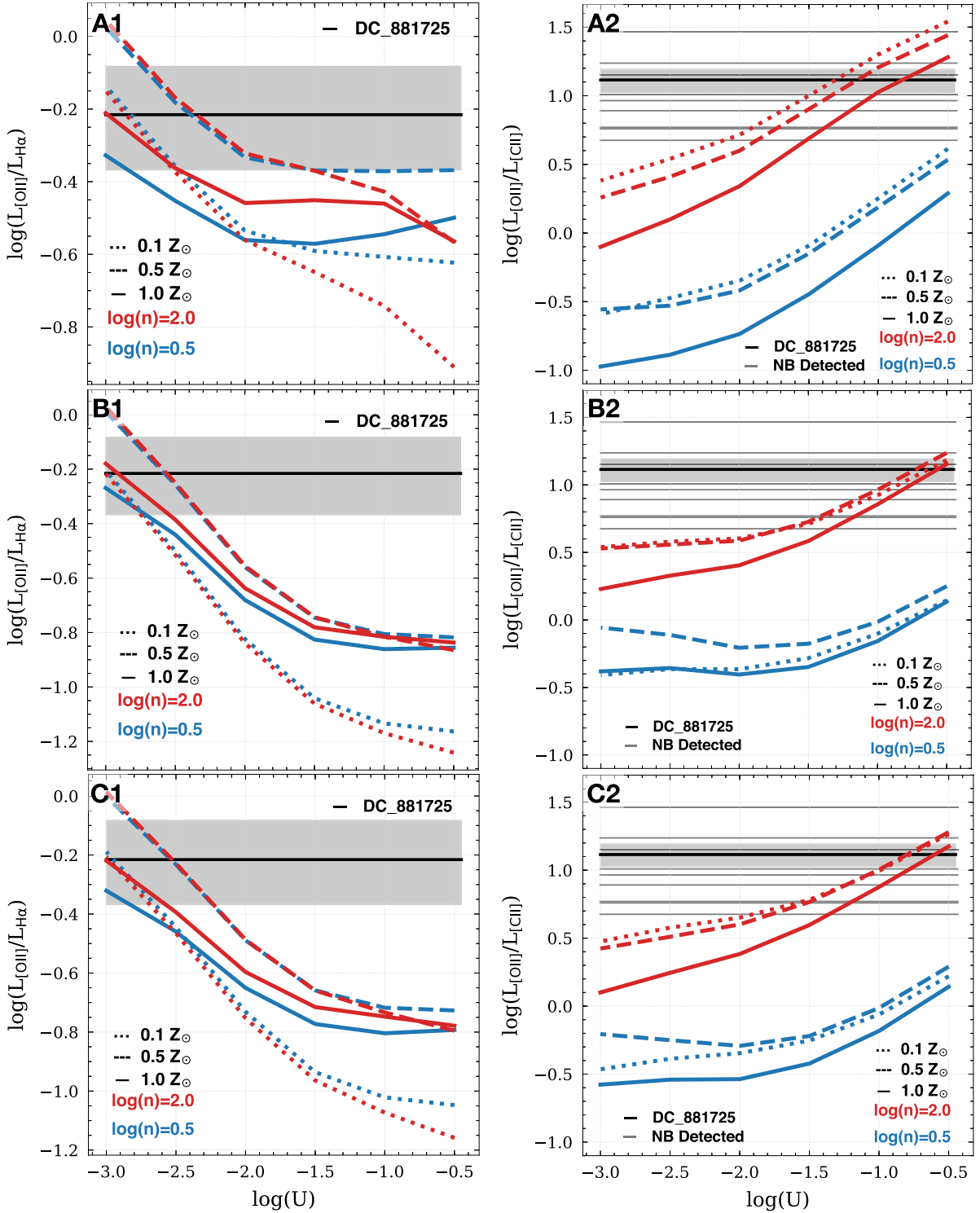[11]Note that $U = q/c$, where $c = 3 \times 10^{10}$ cm s^{-1} is the speed of light.

Figure 6. Predictions of the emission line ratio log ($L_{[O\,II]}/L_{H\alpha}$) (left-hand panel) and log ($L_{[O\,II]}/L_{[C\,II]}$) (right-hand panel) from CLOUDY simulations as a function of ionization parameter (U) for 0.1 $Z_\odot$ (dotted lines), 0.5 $Z_\odot$ (dashed lines), and 1 $Z_\odot$ (solid lines) metallicities as well as hydrogen densities of log ($n/[\mathrm{cm}^3]$) = 0.5 (blue) and log ($n/[\mathrm{cm}^3]$) = 2 (red). The different panels show different assumptions for the background stellar population (see the text): burst of star formation (panels A), constant star formation (B), and best-fitting SED for *DC_881725* (C). Our observed (dust-corrected) line ratios are shown as horizontal lines. In the case of log ($L_{[O\,II]}/L_{[C\,II]}$) (right-hand panels), we show *DC_881725* in black (with the 1σ uncertainty shown as grey swath) and the nine narrow-band detected galaxies as grey lines. For log ($L_{[O\,II]}/L_{H\alpha}$) (left-hand panels), we only show the median line ratio marginalized over all the uncertainties of the individual galaxies (1σ uncertainties shown by the grey swath). Note that the log ($L_{[O\,II]}/L_{H\alpha}$) ratio is largely insensitive to the hydrogen density, hence provides a good constraint on U.

3.2.2 The log (L_{[OII]}/L_{[CII]}) luminosity ratio

Next, we focus on the log $(L_{[O\,II]}/L_{[C\,II]})$ luminosity ratio. The models from CLOUDY are shown in the right-hand panels of Fig. 6. Increasing ionization parameter as well as increasing electron density result in a higher luminosity ratio. On the other hand, more metal-enriched environments are expected to have lower log $(L_{[O\,II]}/L_{[C\,II]})$ ratios. The trends are not significantly affected by the different assumptions on the underlying stellar population.

The black and grey horizontal lines show the measured ratios for *DC_881725* and the nine narrow-band detected galaxies, respectively. The [O II] luminosities have been corrected for dust attenuation using the methods described in Section 3.1.2. We find a log-ratio of $1.11^{+0.08}_{-0.08}$ for *DC_881725* and a median ratio of $0.98^{+0.21}_{-0.22}$ for all 10 galaxies. Note that the true stellar reddening curve plays a subdominant role in this rather quantitative analysis.

The models show that the intrinsic log $(L_{[O\,II]}/L_{[C\,II]})$ luminosity ratio is significantly degenerate with metallicity, ionization parameter, and electron density. From Section 3.2.1 we expect an ionization parameter $\log(U) < -2$. Metallicity seems to have the least impact on the luminosity ratio assuming a reasonable range between 10 per cent solar and solar metallicity. An analysis of the rest-frame UV absorption line strengths (see Section 2.2) suggests that our galaxies have ~ 50 per cent of the solar gas-phase metal enrichment on average. Fixing the metallicity to half-solar is therefore a reasonable assumption. Within these assumptions our measurements would argue for electron densities of $\log(n/[\mathrm{cm}^{-3}]) \sim 2.5\text{--}3$.

Typical electron densities are measured to be around $100 - 200\,\mathrm{cm}^{-3}$ in galaxies with similar rates of star formation at $z \sim 2$. This is about a factor of $5\text{--}10$ higher than observed on average in local galaxies (Masters et al. 2014; Steidel et al. 2014; Sanders et al. 2016; Davies et al. 2021). However, as pointed out by Kaasinen et al. (2017) (see also Shimakawa et al. 2015; Davies et al. 2021), the electron density is positively correlated with (specific) SFR, hence the higher $\log(n)$ found in high-z galaxies are likely due to a higher normalization of the main-sequence (i.e. higher average SFR). In line with this, it was found that $\log(n)$ does not significantly evolve with redshift for SFR-matched samples. Taking the measurements in Davies et al. (2021) at face value suggests at least $\log(n/\mathrm{cm}^{-3}) \sim 2.5$ ($300\,\mathrm{cm}^{-3}$) for the average specific SFR of our sample ($\sim 0.9\,\mathrm{Gyr}^{-1}$) according to $z \sim 2$ galaxies. Our measurements ($\log(n/[\mathrm{cm}^{-3}]) \sim 2.5\text{--}3$) are generally consistent with these expectations given their high *SFRs*, although at the high end. Lower electron densities (e.g. $\sim 100 - 200\,\mathrm{cm}^{-3}$, typical at $z \sim 2$) would indicate ionization parameters of $\log(U) \gtrsim -1.7$, which is clearly inconsistent with our measured log $(L_{[O\,II]}/L_{H\alpha})$ luminosity ratio.

Combining the results of this section with Section 3.2.1, we conclude that our $z \sim 4.5$ galaxies have ionization parameters $\log(U) < -2$ and electron densities $\log(n/[\mathrm{cm}^{-3}]) \sim 2.5\text{--}3.0$. While the former is consistent with measurements in galaxies at $z = 2\text{--}3$, the latter is consistent with or slightly higher than the expected electron densities given the SFRs of our galaxies and the relation between $\log(n)$ and star formation measured in lower redshift galaxies. Significantly higher ionization parameters are suggested for galaxies in the epoch of reionization at $z > 6$, which would argue for a fast evolution of the ISM properties at times earlier than $z \sim 4.5$. Furthermore, we find that these typical main-sequence galaxies are much less extreme than submillimetre galaxies at similar redshifts showing electron densities of $\log(n/[\mathrm{cm}^{-3}]) = 4$ or more (e.g. Bothwell et al. 2017; De Breuck et al. 2019).

We note that nine of the galaxies lie in a greater structure associated with a proto-cluster at $z \sim 4.57$ (Lemaux et al. 2018). It is possible that the proto-cluster environment has altered their properties in some way that could be relevant for this study. For example, Darvish et al. (2015) argues for a lower electron density in galaxies residing in dense environments ($\Sigma/\Sigma_{\mathrm{mean}} > 4$) based on a comprehensive study of an over dense region at $z \sim 0.5$. The translation of this result to (less) overdense regions at $z \sim 5$ and hence the impact of the environment on the properties of our galaxies remains unclear. As far as we can tell, the nine galaxies have statistically indistinguishable properties with respect to the other *ALPINE* (hence field) galaxies using the metrics that we are able to compare (e.g. Fig. 1). As such, it is at least likely that any effect of environment on the ISM is subtle at best.

3.2.3 Caveats

Several other parameters could change the modelled line ratios. Here, we investigate the impact of the stellar metallicity of the stellar population producing the incident spectrum as well as the geometrical covering factor.

First, we ran the simulation with a covering factor of 0.1 instead of 1 and found that it does not have a significant impact (< 0.05 dex) on either line ratio. Secondly, we implemented a solar stellar metallicity (instead of 10 per cent solar) for the incident spectrum produced by the BPASS models. We find that this increases both log $(L_{[O\,II]}/L_{H\alpha})$ and log $(L_{[O\,II]}/L_{[C\,II]})$ ratios by 0.15 dex. This seems to be because a factor 8 decrease in [O II], which is overbalanced by a factor 11 and 12 decrease in Hα and [C II], respectively.

An increase in the log $(L_{[O\,II]}/L_{[C\,II]})$ luminosity ratio would slightly reduce the likelihood of high electron densities for a given ionization parameter. And increased log $(L_{[O\,II]}/L_{H\alpha})$ ratio would further allow slightly higher ionization parameters (especially if assuming a gas-phase metallicity of 50 per cent solar). All in all, a higher stellar metallicity would argue for $\sim 0.2 - 0.3$ dex higher ionization parameters and roughly the same amount of lower electron densities, making our galaxies consistent with their counterparts at $z \sim 2\text{--}3$ with similar star formation properties.

Finally, our simple model assumes that the galaxy is a single H II region. More complicated 'multisector' models could be investigated, however, we do not think that given the uncertainties in our (photometric) measurements of [O II] and Hα this would improve the robustness of our results.

4 CONCLUSIONS

We have assembled the best-studied sample of main-sequence galaxies at $z \sim 4.5$ to date, to investigate key parameters of the ISM as well as the relation between [O II] and total SFR of galaxies in the early Universe right after the epoch of reionization.

The 10 main-sequence galaxies at $z \sim 4.5$ have measurements of rest-frame UV absorption lines, optical [O II] (from spectroscopy and narrow-band imaging) and Hα emission (from *Spitzer*), as well as far-infrared observations of [C II] and dust continuum from ALMA. We use the total SFRs derived from [C II] emission as well as far-infrared continuum to calibrate the relation between SFR and [O II] emission for the first time at these redshifts (Section 3.1). Furthermore, we constrain key parameters of their ISM (metallicity, electron density, ionization parameter) via the UV absorption lines and [O II]/[C II] and [O II]/Hα luminosity ratios, which we compare

to CLOUDY simulations (Sections 2.2 and 3.2). Our findings can be summarized as follows:

(i) The relation between dust-corrected [O II] luminosities and total SFR is best described by subsolar metallicity models from Kewley et al. ([2004](#)). For the median of our sample, we find a total SFR of $53.57^{+23.48}_{-31.30}\,\mathrm{M_\odot\,yr^{-1}}$ and $\log(L_{\mathrm{[OII]}}/\mathrm{L_\odot}) = 9.88^{+0.29}_{-0.51}$. The original Kennicutt ([1998](#)) [O II]−SFR relation would overestimate the SFR by a factor of ∼3 (Section 3.1.2).

(ii) By comparing the $\log(L_{\mathrm{[OII]}}/L_{\mathrm{[CII]}})$ and $\log(L_{\mathrm{[OII]}}/L_{\mathrm{H\alpha}})$ luminosity ratio to CLOUDY models, we find that our galaxies have ionization parameters $\log(U) < -2$ and electron densities of $\log(n/[\mathrm{cm}^3]) \sim 2.5$–3. The former is consistent with $z \sim 2$–3 galaxies, the latter may be slightly higher than expected based on our galaxies' specific SFR. However, these results depend on the input parameters for the CLOUDY simulation. Specifically, increasing the stellar metallicity of the incident spectrum from 10 per cent solar to solar would make our observations more consistent with electron densities measured in $z = 2$–3 galaxies.

All in all, we find that the ISM properties of this representative sample of $z \sim 4.5$ galaxies are similar to their descendants at $z \sim 2$–3 when matched by their specific SFRs. There are indications that the ionization parameter of more primordial galaxies in the epoch of reionization at $z > 6$ is increased (see e.g. Harikane et al. [2020](#)) compared to our findings. This suggests a rapid evolution of the ISM in the few 100 Myr spanning these epochs. The relation between [O II] emission and SFR is consistent if assuming a gas-phase metallicity of ~ 50 per cent solar, which is in line with the estimates from rest-frame UV absorption spectroscopy. This result is an important step towards using optical emission lines as total SFR indicators in the era of *JWST*.

In this work, we demonstrated the necessity the combination of data from many facilities covering the rest-frame UV to far-infrared to decipher the physical properties of high-redshift galaxies. Although this is the largest and best-studied sample of typical $z \sim 4.5$ galaxies to-date, larger samples with similar multiwavelength observations are crucial for a better statistical study of the dependence of the reported parameters on other galaxy properties. Larger surveys with current facilities (e.g. *Keck*) and later *JWST* will provide these samples.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: ABSOLUTE FLUX CALIBRATION OF THE *MOSFIRE* SPECTRUM

For the absolute calibration of the *MOSFIRE* spectrum, we use a 17th magnitude standard star from the 2MASS star catalogue, which was included for this purpose in the mask. The 1D spectrum of the star is extracted within 10 pixels (1.8 arcsec) around the centre of the continuum emission on the 2D spectrum in e⁻/s. The wavelength-dependent calibration is then derived by comparing the observed spectrum with models of different stellar spectral types.

In detail, we use the spectra from the Pickles (1998) stellar model library, which offers a wide range in spectral types from O to M and covers a wavelength from $0.115 - 2.5\,\mu\mathrm{m}$ in steps of 5 Å. This is sufficiently red to match the *MOSFIRE K* −band. We find that the spectrum at $> 2\,\mu\mathrm{m}$ only changes slowly as a function of stellar type, hence we only focus on a coarse grid including O5 V, B3 V, A5 V, F5 V, G5 V, K5 V, and M5 V type stars. The model

spectrum of each of these is normalized to the UltraVista $K-$band flux of the observed 2MASS star, obtained from the *COSMOS2015* catalogue (McCracken et al. 2012; Laigle et al. 2016). A wavelength-dependent conversion from units of $e^-\,s^{-1}$ to $erg\,s^{-1}\,cm^{-2}\,\text{Å}^{-1}$ is then derived by comparing the normalized model spectrum to the observed spectrum of the 2MASS star. The resulting normalizations are shown in Fig. A1. The arrow indicates the wavelength of [O II]. The computed normalization is within 5 per cent for all spectral types except the coolest M-dwarf. By comparing the $K-$band normalized stellar spectra to the UltraVISTA Y, J, and H photometry, we find that our standard star fits best a G−type star. We therefore use the G5 V normalization through out the paper.

APPENDIX B: COMPARISON OF OPTICAL EMISSION LINE MEASUREMENTS TO *EL-COSMOS*

We derived the H α luminosities for our 10 galaxies from their *Spitzer* [3.6 μm] − [4.5 μm] colours (see Faisst et al. (2020a) and Faisst et al. (2016a) for a detailed description of the methods used). Here we compare our measurement to the recent *EL-COSMOS* catalogue (Saito et al. 2020), which provides predictions of the intrinsic (dust-corrected) [O II] and H α optical lines from SED fitting calibrated to spectroscopic measurements for all galaxies in the Laigle et al. (2016) *COSMOS2015* catalogue. Our luminosity measurements have been dust corrected using the method described in this paper. Fig. B1 shows the result of the comparison. *EL-COSMOS* agrees very well with our narrow-band and spectroscopic [O II] measurements. Comparing the H α measurements, we find a good agreement within a factor of 2. Note that we marked galaxies that have uncertain H α measurements due to contaminated *Spitzer* photometry (see also Faisst et al. 2020a).

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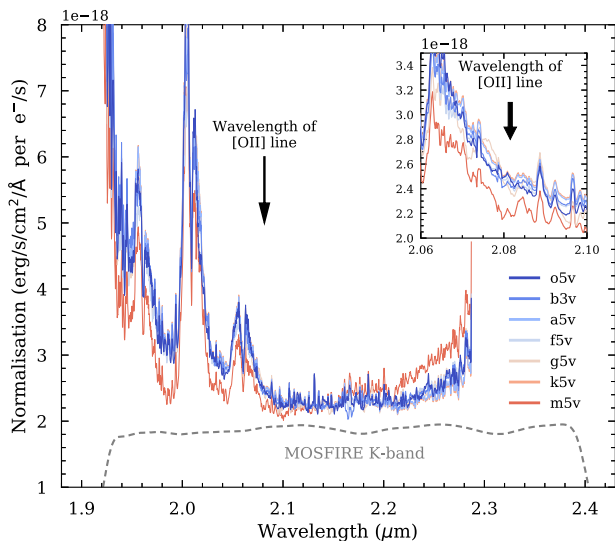
Figure A1. Wavelength-dependent normalization of the *MOSFIRE*/K band spectrum derived for various stellar types from the Pickles (1998) library. Our standard star is close to a G5 V type. The wavelength of [O II] for *DC_881725* is indicated by an arrow. The dashed line represents the wavelength range of the *MOSFIRE K*-band.
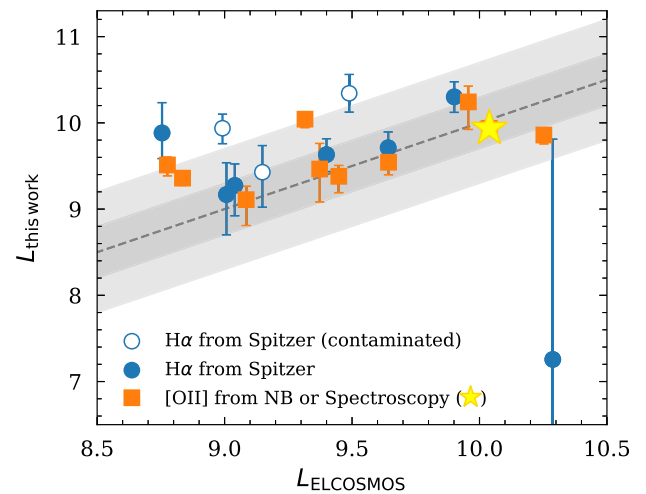

Figure B1. Comparison between our measurements of H α (blue circles, derived from *Spitzer* colours) and [O II] (orange squares, derived from narrow-band imaging or spectroscopy) and the derivations in the *EL-COSMOS* catalogue. Galaxies whose H α measurements are uncertain due to contaminated *Spitzer* photometry are shown as open circles. The dark (light) grey areas denote deviations of a factor of 2 (5) from the 1−to−1 relation (dashed line).

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