First look with JWST spectroscopy: \( z \sim 8 \) galaxies resemble local analogues

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ABSTRACT

Deep images and near-IR spectra of galaxies in the field of the lensing cluster SMACS J0723.3-7327 were recently taken in the Early Release Observations program of JWST. Among these, two NIRSpec spectra of galaxies at \( z = 7.7 \) and one at \( z = 8.5 \) were obtained, revealing for the first time rest-frame optical emission line spectra of galaxies in the epoch of reionization, including the detection of the important \([\text{O} \, \text{iii}] \lambda 4363\) auroral line (see JWST PR 2022-035). We present an analysis of the emission line properties of these galaxies, finding that these galaxies have a high excitation (as indicated by high ratios of \([\text{O} \, \text{iii}] \lambda 5007/\lambda 4372\), \([\text{Ne} \, \text{v}] \lambda 3869/\lambda 4651\)), high equivalent widths, and other properties which are typical of low-metallicity star-forming galaxies. Furthermore, we show that the galaxy spectra at \( z \sim 8 \) reveal a strong resemblance of the emission lines properties of galaxies in the epoch of reionization with those of relatively rare local analogues previously studied from the SDSS. Clearly, these first JWST observations demonstrate already the incredible power of spectroscopy to reveal properties of galaxies in the early Universe.

Key words. Galaxies: high-redshift – Galaxies: ISM – Cosmology: dark ages, reionization, first stars

1. Introduction

Optical emission line spectroscopy has long provided important insights on the physical composition, properties of the interstellar medium (ISM), and the nature of the ionizing power of galaxies, yielding thus key information to understand many key aspects of galaxy evolution (see review of Kewley et al. 2019). The well-known emission lines of H, He, O, N, S, Ne, and other elements detected in optical galaxy spectra, emitted in the ionized ISM (HII regions primarily) have been detected in nearly one million galaxy spectra, out to redshifts of \( z \sim 0.5 \) – 1 with the Sloan Digital Sky Survey (SDSS, Alam et al. 2020). Ground-based near-IR spectroscopy has recently pushed these limits to \( z \sim 1.5 \) – 3, where ~1500 measurements of the strongest rest-optical lines have been possible, e.g. with the MOSDEF survey (Kriek et al. 2015), revealing thus ISM properties at cosmic noon (e.g. Forster Schreiber & Wuyts 2020). The recent launch of the JWST and the spectroscopic capabilities of its NIRSpec multi-object spectrograph in the near-infrared opens now a completely new window into the early Universe, where, for the first time, all the “classical” optical diagnostics developed at low-z can be used to study the properties of galaxies over a wide redshift range, from \( z \sim 3 \) out to the epoch of reionization (\( z > 6.5 \)).

The first public NIRSpec observations, part of the Early Release Observations (ERO) of JWST, have covered the SMACS J0723.3-7327 galaxy cluster, providing 1.8 - 5.2 \( \mu \)m spectra of 35 objects in the field. Among those, three galaxies in the epoch of reionization were observed, showing spectacular, rich rest-frame optical emission line spectra of objects at \( z = 7.7 \) and \( z = 8.5 \) (see JWST Press release 2022-035\(^1\) and Carnall et al. 2022). We here report the first determination of the metallicity (O/H) of these galaxies, a detailed analysis of their emission line properties, and a comparison with observed properties of low-z emission line galaxies.

In Sect. 2 we describe the observational data, reduction and measurements, used in this work. In Sect. 2 we examine the observed emission line properties of the three \( z \sim 8 \) galaxies, determine their oxygen abundance and compare them to low-redshift comparison samples. We also discuss the preliminary mass-metallicity relation and other physical properties of these galaxies. Our main results are summarised in Sect. 4.

2. Observations

2.1. JWST NIRSpec observations

Rest-frame UV and optical spectra were obtained on 30 June 2022 using the NIRSpec instrument with the micro-shutter assembly (MSA). Observations consist of two different pointings (s007 and s008), each of them using two grating/filter combinations.

\(^1\) https://webbtelescope.org/contents/news-releases/2022/news-2022-035

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tions: G235M/F170LP and G395M/F290LP. The total exposure time is 2×8754 seconds for each grating/filter. This provides a spectral resolution $R \approx 1000$ and a continuous spectral coverage of $\approx 1.75 - 5.20 \mu$m. Fully calibrated spectra (calibration level 3) were retrieved from the Mikulski Archive for Space Telescope (MAST) which were previously processed with the JWST Science Calibration Pipeline (calver=1.5.3 and crds_ctx: jwst-0916.pmap). For each source, two individual 1D spectra (s007 and s008) are combined using the average flux, and after masking spectral regions affected by cosmic rays and other artifacts. An example of the combined spectrum of 06355 at $z \approx 7.7$ is shown in Fig. 1.

The spectra of the three sources show nebular emission lines, many of them detected with high significance ($> 3\sigma$). These include Balmer lines (Hβ, Hγ, Hδ, [O ii], [O iii], [Ne ii], and He i). In particular, the auroral [O ii]λ4363 line – key for accurate determinations of the O/H abundance using the direct method – is detected in all galaxies with a significance of $3.9 - 5.7\sigma$. Gaussian profiles are fitted to each line using the Python non-linear least-squares function curve-fit, and assuming a constant level for the continuum ($f_0$). We derive the redshifts for these sources using the brightest lines, namely Hγ, Hδ, and [O iii]λ4959,5007 lines (Table 1). The continuum is clearly detected in the two $z \approx 7.7$ sources (10612 and 06355, see Fig.1) allowing the determination of the equivalent widths of the lines (Table 1). However, these do not include any correction for slit-losses and other possible effects due to different morphologies of the continuum emission and nebular lines.

After careful inspection of the flux measurements we noticed that some line ratios have nonphysical values, suggesting systematics on the flux calibration and throughput in the current JWST pipeline. For example, the observed Balmer line ratios are found to be larger than the intrinsic Hγ/Hβ and Hδ/Hγ ratios assuming case B recombination. Before more accurate calibration reference files are available, we overcame this issue by applying an ad hoc correction to the flux calibration. More specifically, we fit a power law ($\propto \lambda^x$) to i) the intrinsic Hγ/Hβ = 0.47 and Hδ/Hγ = 0.26 (case B) and to ii) the observed line ratios. The correction factor as a function of wavelength is thus given by the division between i) and ii) for each source, and it is applied to the full spectral range covered by the G235M/F170LP grating/filter configuration. This empirical correction results in a maximum increase of $\sim 20 - 50\%$ (depending on galaxy) for the O32=[O iii]λ5007/O ii]λ3727 ratio, and smaller corrections for other line ratios. By doing this, we are also applying a first-order correction to the Balmer decrement, thus losing the information on the dust attenuation. Given the uncertainties on the flux calibration and on our empirical correction, we conservatively add 20% of uncertainties on our flux measurements. Nevertheless, our analysis will focus mostly on lines ratios between nearby lines (see Section 3), thus minimizing possible issues on the flux calibration.

### 2.2. JWST NIRCam observations

We make use of a single NIRCam pointing in the six wide filters F090W, F150W, F200W, F277W, F356W, and F444W, with a uniform exposure time of 2.1 hr in each, and shallower NIRISS filter configuration. This empirical correction results in a maximum increase of $\sim 20 - 50\%$ (depending on galaxy) for the O32=[O iii]λ5007/O ii]λ3727 ratio, and smaller corrections for other line ratios. By doing this, we are also applying a first-order correction to the Balmer decrement, thus losing the information on the dust attenuation. Given the uncertainties on the flux calibration and on our empirical correction, we conservatively add 20% of uncertainties on our flux measurements. Nevertheless, our analysis will focus mostly on lines ratios between nearby lines (see Section 3), thus minimizing possible issues on the flux calibration.

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1. https://s3.amazonaws.com/grizli-v2/SMACS0723/Test/image_index.html
2. https://github.com/gbrammer/grizli/
3. https://github.com/gbrammer/grizli/
which should mainly be due to consistently younger ages found by these authors. Before more detailed analyses of the SEDs and spectra of these galaxies become available, we adopt the stellar masses from our preferred CIGALE fits and a conservative uncertainty of ±0.3 (see Table 1). To correct the masses for gravitational magnification from the cluster, we use the magnification factors $\mu$ from the lens models of Caminha et al. [2022]. Other lens models, e.g. those used by Carnall et al. [2022], yield similar magnifications (differences of 10-50% at most) for the sources studied here.

2.3. Comparison samples

For comparison with low-$z$ galaxies we use a sample of 5607 star-forming galaxies from the SDSS Data Release 14 compiled by Y. Izotov and collaborators, analysed in earlier publications (e.g. Guseva et al. [2019] Ramabrosan et al. [2020]). The selection criteria used for the extraction of star-forming galaxies are presented in Izotov et al. [2014]. Then we require a detection of the $[O\text{ III}]_{5007}$ line with an accuracy better than 4σ, allowing thus direct abundance determinations using the $T_e$-method. Subsequently we refer to this sample as Izotov-DR14.

We also use the spectra of 89 galaxies at $z \sim 0.3$ from the Low-Z Lyman Continuum Survey (LzLCS), the first large sample of galaxies with UV spectroscopy covering both the Lyman continuum and non-ionizing UV (see Flury et al. [2022a,b]). Approximately half of the sample has $[O\text{ III}]_{4363}$ detections.  

3. Observed and derived properties of the $z \sim 8$ galaxies

3.1. Emission line properties

First we examine the observed emission line ratios in the three high-$z$ galaxies and compare them to those of the low-$z$ samples (cf. above). Figure 2 shows the main line ratios including the lines of $[Ne\text{ II}]_{3869}$, $[O\text{ II}]_{4372}$, $[O\text{ III}]_{4363}$, $[O\text{ III}]_{5007}$, and $H\alpha$ lines, which are detected in the JWST spectra. The $[Ne\text{ II}]_{[O\text{ II}]}$ (Ne3O2) ratio is well known to closely trace $O_3^{+}$, since both high ionization lines of $[Ne\text{ II}]$ and $[O\text{ II}]$ originate in the same zone of the region. Our measurements in the high-$z$ galaxies are compatible with the observed correlation, providing confidence for our empirical flux calculation. The $z = 8.5$ galaxy 04590 differs somewhat from the majority of points in this and other diagrams, which is probably due to a remaining inconsistency in the data reduction/calibration. By these line ratios, the three high-$z$ galaxies are found to be relatively high excitation, with $[O\text{ III}]_{4363}$ and $[O\text{ III}]_{5007}$ $\sim 5000$ Å in the brightest source.

The detection of the auroral $[O\text{ III}]_{4363}$ line and $[O\text{ II}]_{4363}$ provides access to the electron temperature $T_e$, and thus allows abundance determinations using the so-called “direct method” (see e.g. Kewley & Dopita [2002]). To do this we follow the prescriptions of Izotov et al. [2006] assuming low densities. The results are listed in Table 1. We find electron temperatures $T_e \sim 16000 - 18000$ K for the two $z = 7.7$ galaxies, and nebular O/H abundances of 12 + log(O/H) = 7.85 for the two objects. This includes both ionic abundances of $O^+$ and $O^{2+}$, determined from the optical lines; in both cases $O^{+}$ dominates. For 04590 the unusually low $[O\text{ III}]_{4363}/[O\text{ II}]_{λ5007}$ ratio leads to unphysically high electron temperatures, indicating possibly a data reduction problem. Assuming a typical $T_e = 16000$ K, we obtain 12 + log(O/H) = 7.50 for 04590, and 12 + log(O/H) $\sim$ 8.0 $\pm$ 0.1 for the other galaxies. Finally, we also use the strong line method of Izotov et al. [2021b] for low metallicities, obtaining 12 + log(O/H) = 7.36 for 04590. The O/H abundances agree also with those derived using strong line methods.

In Fig. 3 we show the Ne3O2 and $[O\text{ III}]_{4363}/H\gamma$ ratios as a function of metallicity for the low-$z$ samples and the three $z \sim 8$ galaxies. We use these line ratios which are close in wavelengths to minimize possible uncertainties of the flux calibration, differential slit losses and others. Empirically, these line ratios can also provide a simple estimate of the metallicity O/H, as discussed by earlier studies (see e.g. Nagao et al. [2006], Sanders et al. [2020]). In any case, we see that our metallicity estimates of the high-$z$ galaxies lead to fairly compatible locations in these diagrams. We conclude that the three $z \sim 8$ star-forming galaxies have low metallicities, in the range of 12 + log(O/H) $\sim$ 7.4 $-$ 7.9. More accurate determinations, including a proper evaluation of the uncertainties, await proper calibrations and a more sophisticated data reduction.

Table 1. Observed and derived quantities for the three high-$z$ galaxies

| Quantity | 04590 | 06355 | 10612 |
|----------|-------|-------|-------|
| redshift $z$ | 8.495 | 7.664 | 7.660 |
| $T_e$(OII)$^\alpha$ | 15995 | 18700 |
| 12 + log(O/H)$^\alpha$ | 7.85 | 7.85 |
| 12 + log(O/H)$^\beta$ | 7.50 | 8.0 |
| 12 + log(O/H)$^\gamma$ | 7.36 | 7.91 |
| O32 | 7.0 | 6.3 | 10.6 |
| EW([O III]$_{5007}$) | 172 ± 150 | 723 ± 78 | 638 ± 176 |
| $\beta_{[O\text{ III}]}$ | 27.8 | 26.6 | 25.6 |
| $M_{1500}^\alpha$ | -20.29 | -21.09 | -20.38 |
| $M_{1500}^\beta$ | -18.06 | -20.51 | -19.81 |
| $\beta_{1350}$ | -2.20 ± 0.15 | -1.96 ± 0.22 | -2.31 ± 0.11 |
| log([M$_{\odot}$]) $\times \mu$ | 9.0 ± 0.3 | 9.2 ± 0.3 | 8.9 ± 0.3 |
| Magnification $\mu$ | 7.9 | 1.7 | 1.7 |

$^\alpha$ direct method, $^\beta$ assuming $T_e$ = 16000 K $^\gamma$ using strong line methods (Izotov+2019,2021) $^\gamma$ observed, including lensing $^\gamma$ corrected for lensing

Since the continuum is also detected in the NIRSpec spectra of the two $z = 7.7$ galaxies, and very weakly so also in the third object, we have also measured the $[O\text{ III}]_{λ5007}$ equivalent width (see Table 1). We compare our measurements with those from the low-$z$ galaxies in Fig. 4, where strong correlations between EW([O III]$_{5007}$) and properties such as O32, Ne3O2, and others have been found (Tang et al. 2019; Izotov et al. 2021a). Possibly, the high-$z$ sources are somewhat offset. In any case, the EWs are high in the galaxies with significant continuum detections, with EW([O III]$_{λ5007}$) $\sim$ 700 Å in the brightest source.

Empirically, the ionizing photon production efficiency, $\xi_{ion}$, is found to increase with the $[O\text{ III}]_{λ5007}$ equivalent width, as also shown in Fig. 4. Using the relations found at low-$z$ and $z \sim 1 - 2$ (see Tang et al. 2019; Izotov et al. 2021a), we estimate log($\xi_{ion}$) = 25.1 $-$ 25.5 erg s$^{-1}$ Hz$^{-1}$, up to a factor $\sim$ 2 higher than the “canonical” value often assumed in ionizing photon budget calculations (Robertson et al. 2013). This is comparable to other estimates of $\xi_{ion}$ at high redshift (e.g. Stefanon et al. 2022).
3.2. Physical properties of the $z \sim 8$ galaxies and the mass-metallicity relation

As discussed, the three $z \sim 8$ galaxies show emission line properties comparable to compact star-forming galaxies at low-$z$ with strong emission lines. Izotov et al. (2021a) have shown that the low-$z$ galaxies with strong lines (EW(Hβ) $> 100$ Å) are good analogues of many of the $z \sim 1 - 3$ star-forming galaxies (Lyman alpha emitters and Lyman break galaxies) studied so far. By inference the emission line properties of the three $z \sim 8$ galaxies
studied here therefore also resemble those at intermediate redshifts.

By construction, the galaxies selected here cannot be claimed to be “typical”, and larger, systematic studies will be needed. One object, 10612, shows a very high ratio [O III]/λ5007/Hβ = 10.1 and a strong [O II]/λ4363 line, which could indicate an active galaxy (Seyfert 2). On the other hand, we clearly find evidence for one star-forming galaxy with a fairly low metallicity (04590 with 12 + log(O/H) ≈ 7.4 ± 0.1).

If we combine our nebular metallicity estimates with the stellar masses described earlier, we obtain the mass-metallicity relation shown in Fig. 5. Our objects are found close to or below the mass-metallicity relation observed at z ∼ 2 and possibly offset by ~ 0.2 – 0.3 below this relation, in good agreement with the relation derived by Ma et al. (2016) from simulations. Similar results were also obtained by Jones et al. (2020) using an indirect method based on ALMA emission line detections. At the present stage we consider the stellar masses uncertain, since these depend significantly on assumptions of the star formation history and on the age of stellar populations. For example, the masses derived from SEDs by Carnall et al. (2022) are consistently lower than our estimates, which would imply that our z ∼ 8 galaxies lie close to the z ∼ 2 mass-metallicity relation, as shown in Fig. 5. The lower masses are mostly due to the very young ages (~ 1 – 2 Myr) inferred by these authors, whereas our SED fits favour less extreme populations. Although Carnall et al. (2022) claim that the SEDs show evidence for Balmer jumps (i.e. Balmer breaks in emission due to strong nebular continuum), we do not see such a behaviour in the NIRSpec spectrum of the brightest source, 06355, shown in Fig. 1.

Having shown that the z ∼ 8 galaxies closely resemble strong emission line galaxies from our low-z sample it is tempting to infer indirectly other properties using correlations established at low-z. Certainly, the high O32 ratios, low metallicity, and blue UV slopes (β) suggest that these galaxies could contribute to cosmic reionization, i.e. have escaping ionizing photons. For example, for the observed values of O32, 12 + log(O/H), and β, the LzLCS results suggest a 30-60% detection fraction of the Lyman continuum. Adopting the mean relation between the LyC escape fraction, fesc, and the UV slope, we estimate fesc = 0.03 – 0.08 for the three z ∼ 8 galaxies, although the LyC escape could also be significantly higher (see Chisholm et al. 2022).

Future improvements in the calibration and data reduction and additional observations will allow us to determine more accurately equivalent widths and total line fluxes of emission lines, measure continuum shapes, combine photometry and spectra etc. and hence improve our knowledge of the physical properties of galaxies at high-redshift.

4. Conclusion

We have analysed the rest-frame optical spectra of two galaxies at z = 7.7 and one at z = 8.5 from the JWST Eearly Release Observations. The spectra exhibit numerous emission lines of H, He i, [O II], [O III], and [Ne III], as commonly found in metal-poor star-forming galaxies at low redshift. They provide, for the first time in the epoch of reionization, detailed information on the chemical composition and interstellar medium of these galaxies. Our main results are summarized as follows:

- The auroral [O III]/λ4363 line is significantly detected in all galaxies with 3.9 – 5.7σ, allowing the determination of the O/H abundance (metallicity) using the direct method. Using different methods we find metallicities between 12 + log(O/H) = 7.36 – 7.85, i.e. ~ 5 – 15 % of solar, with typical uncertainties of ~ 0.1 dex.
- All three galaxies show a high excitation, as measured by their line ratios of O32 = 6 – 11 and Ne3O2 = 0.4 – 0.7. The observed emission line ratios are similar to those of rare low-z star-forming galaxies, which are considered analogues of high-redshift (z ∼ 1 – 3) galaxies. One of the z = 7.6 galaxies shows unusually high [O III]/λ5007/Hβ = 10.1, possibly indicative of nuclear activity (Seyfert 2).
- The z ∼ 8 galaxies show quite high equivalent widths, e.g. EW([O III]/λ5007) up to 725 Å, as expected from low-z galaxies with high excitation. Such galaxies are known to be efficient producers of ionizing photons. We conservatively estimate log(fesc) = 23.5 – 25.5 erg -1 Hz for our galaxies.
- Using stellar mass estimates from SED fits, we find the z ∼ 8 galaxies to lie close to or below the mass-metallicity relation (MZR) at z ∼ 2. To assess if the MZR continues to evolve from z = 2 to 8 will need detailed and robust mass determinations and larger galaxy samples.

Overall, the first analysis of the rest-frame optical spectra of galaxies at z ∼ 8 indicates that the emission lines properties of galaxies in the epoch of reionization resemble those of relatively rare “local analogues” previously studied from the SDSS, and for which numerous physical properties have already been determined. These low-z samples will soon be rivaled by numerous measurements with NIRSpec onboard JWST. Clearly, the first data release reveals already an extremely promising “preview” of upcoming science with JWST in the early Universe.

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