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A 2D spatially-resolved study of local analogs of high-z galaxies

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Abstract

The identification and further study of local analogs of high-z galaxies is key to shedding light on the early Universe and the conditions under which the first sources reionized the intergalactic medium. Local analogs have been historically analyzed from their integrated spectra, but recent IFU observations have provided important insights into the interstellar medium (ISM) morphology and how the ionizing radiation escapes from these galaxies. Here we present the first results of a 2D spatially-resolved study of local analogs performed with MEGARA/GTC. We exploited the capabilities of the MEGARA instrument to investigate the nature of these sources as reionization-era analogs through the spatial distribution analysis of their physical and kinematical properties. We estimated the escape fraction of ionizing radiation in different regions and found significant spatial variations which is a signature of the ISM porosity. We tested the Lyman Continuum-leaker status of the galaxies by using indirect indicators based on emission-line ratios, and the results are in good agreement with JWST observations of galaxies at $z > 7$. Furthermore, we provide a recipe to carefully estimate and generate 2D maps of random uncertainties associated with any parameter that can be derived using MEGARA IFU data, and whose approach can be applied to any 2D spectroscopic dataset. This work highlights the powerful capabilities of MEGARA to carry out a detailed scanning of the ionizing structure of the ISM and thus providing useful hints about cosmic reionization.

1 Introduction

Cosmic reionization marks the transition of the Universe from a neutral to an ionized state, holding crucial insights into the formation and evolution of galaxies. To investigate the conditions under which the first sources contributed to ionizing the intergalactic medium (IGM), it is necessary to measure the amount of ionizing radiation that escapes from galaxies, i.e., the escape fraction (f_{esc}) of Lyman continuum (LyC) photons. Since directly detecting this emission from galaxies during the epoch of reionization is impossible due to the absorption produced by the neutral gas in the IGM ([28]), many authors have focused on identifying low-z galaxies that emit LyC photons (known as LyC leakers or LyC emitters). Some of these star-forming galaxies are considered local analogs of high-z galaxies due to their similar properties: small sizes, high star formation rates, high gas content, low dust attenuation, low stellar mass, and low metallicities ([20]). These features make them ideal laboratories for studying the mechanisms that drove cosmic reionization. In addition, although LyC leakers have been historically analyzed from their integrated spectra, a recent study employing Integral Field Spectroscopy (IFS) has shown that single sightline observations may not accurately trace the average escape fraction ([26]). It is therefore essential to study local analogs by spatially-resolved observations to provide insights into the physical processes that enable ionizing photons to escape from these galaxies.

In this work, we selected four galaxies that are considered excellent local analogs of high-z galaxies and potential LyC leakers based on observations and simulations ([29, 16, 20]). However, none of them have been observed using IFS so far. We aim to investigate the nature of these sources as reionization-era analogs through the spatial distribution analysis of their physical and kinematical properties, mapping the ionizing structure of the interstellar medium (ISM), identifying regions that may leakage LyC photons, and testing their resemblance with the high-z galaxy population.

2 Observations and data reduction

This work is based on data taken with the MEGARA instrument, which is installed at the 10.4m Gran Telescopio Canarias (GTC) in the Roque de los Muchachos Observatory. We employed the Integral Field Unit (IFU) mode of MEGARA, which provides a field of view of $12.5'' \times 11.3''$ with a plate scale of $0.62''$/spaxel. The data were obtained in service mode between the semesters 2022A−2024A (PI: C. Cabello). The targets were the dwarf starburst galaxies UM461, UGCA 410, Mrk1450, and LEDA 139572. In order to cover a wide wavelength range, three different gratings were used for each pointing: VPH405-LR, VPH480-LR, and VPH675-LR, corresponding with a resolving power of R = 5000 − 5900. This configuration allows for spatially-resolved observations with high spectral resolution, enabling detailed analysis of the emission lines and providing critical information about the properties and ionizing structure of these local analogs.

The MEGARA Data Reduction Pipeline (DRP[1]) was used to reduce the raw data following

[1]https://guaix-ucm.github.io/megaradrp-cookbook/index.html

the standard steps. The final 2D Row-Stacked Spectra (RSS) FITS files were converted into 3D data cubes of $0.4''$ squared pixel size.

3 Estimation of random uncertainties

To overcome one of the limitations of the MEGARA DRP, which does not provide uncertainties during the calibration procedure, we used the Python code developed in [6] to estimate the random uncertainties associated with the different parameters derived from the MEGARA data. The methodology is based on the numerical approach described in [7] and can be applied to any spectroscopic 2D dataset. We applied the Monte Carlo method to generate synthetic raw MEGARA images (for both calibration and science frames) which are taken as the input of the MEGARA DRP, resulting in a synthetic reduced image. This process is repeated multiple times to generate reduced data cubes that we analyzed following the same procedure as the real data. Finally, we took the standard deviation of the different measurements as the uncertainty of each parameter. The Python code is publicly available on GitHub[2] and the official website of GTC[3].

4 Study of the ISM conditions

This work traced the sub-kpc variations of the complex internal structures of a sample of local analogs revealing that the spatial distribution of the ISM conditions (electron temperature, electron density, ionization parameter, oxygen abundance) is not homogeneous or isotropic. We analyzed the nebular emission in our galaxy sample using different optical emission-line ratios to study the ISM porosity and the spatial variations of indirect indicators of LyC leakage ([12, 14, 28]).

The electron temperatures (Te) were calculated from the ratio of the auroral line [OIII]λ4363 to the nebular [OIII]λ5007 ([23]), and the electron densities were estimated from the ratio of the [SII]$\lambda\lambda$6717, 6731 emission lines using the PyNeb code ([18]). We estimated the oxygen abundances from the direct Te-method following the relations derived by [1, 25]. The ionization parameter was computed from different estimators based on emission-line ratios ([9, 10]). Despite the spatial inhomogeneities found in these extreme systems, they exhibit subsolar metallicities ($Z \leq 0.2\, Z_{\odot}$ assuming $Z_{\odot} = 8.69$, [2]) and ionization parameter values ($-3.0 < log(U) < -1.5$) compatible with reionization-era galaxies.

Overall, the galaxies in our sample follow the trend established by typical local galaxies in the different diagnostic diagrams, which is in good agreement with the observations of high-z galaxies, Green Pea sources, and low-z LyC leakers from the literature ([21, 22, 24]). The outcomes indicate that photoionization from stellar sources is the dominant excitation mechanism in these galaxies. In addition, our galaxy sample exhibits high O32 ratios, which is a necessary (but not sufficient) condition for LyC leakage ([15, 14]). Note that despite being local galaxies, they do not populate the same region of the SDSS low-z sample in the

[2] `https://github.com/criscabe/MEGARA`

[3] `https://www.gtc.iac.es/instruments/megara/#MEGARA_uncertainties`

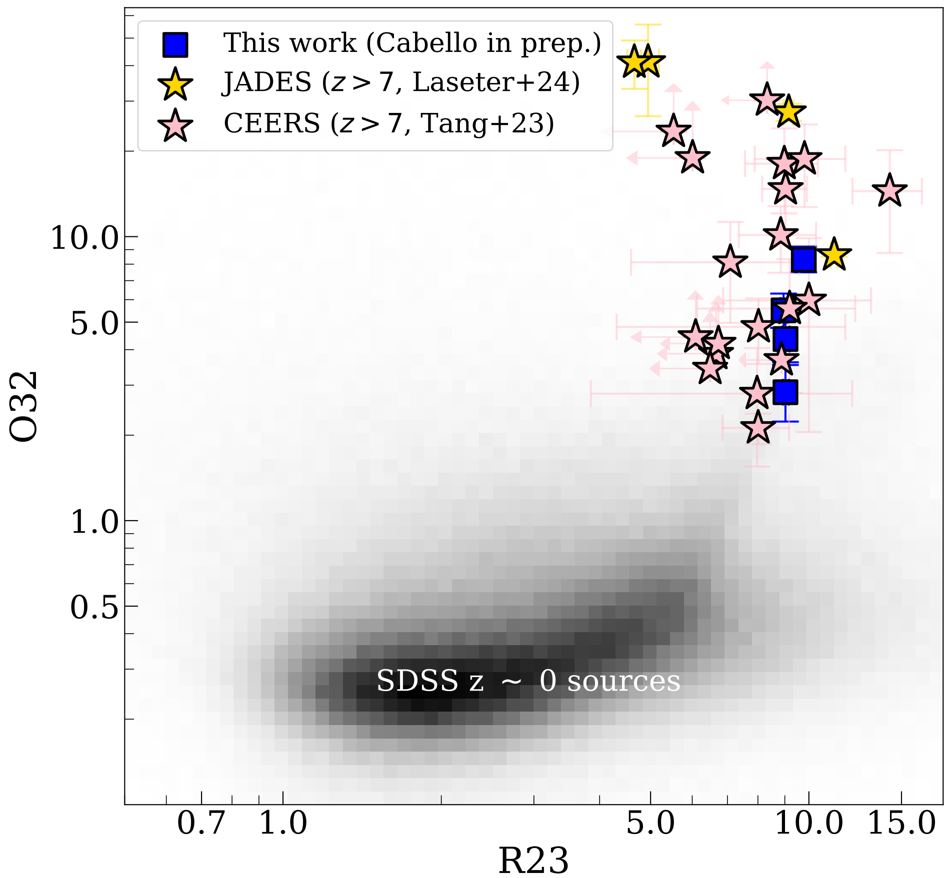

Figure 1: R23 – O32 diagram for our sample of local analogs (blue squares) in comparison with other works to probe the ionization and excitation of the ISM. Yellow and pink stars represent a subsample of high-z ($z > 7$) sources observed with the JWST in the JADES ([17]) and CEERS ([27]) surveys respectively. The gray shadow represents SDSS local galaxies.

excitation-ionization diagrams. In contrast, these results are consistent with the measurements of $z \sim 7-9$ galaxies observed with the James Webb Space Telescope (see Fig. 1), which reinforces the status of our sample as excellent analogs of the high-z galaxy population (Cabello et al. *in prep.*).

Furthermore, we used the `astrodendro` package to identify regions at different levels of surface brightness (e.g.,[19, 11]). Then, we extracted the spectral information from the spatially distinct apertures and compared the results with those obtained from the integrated spectrum. Finally, we estimated f_{esc}(LyC) using the O32 relation for known low-z LyC leakers derived by several authors in the literature ([8, 13]). We found significant differences between apertures, suggesting the presence of optically thin channels through which most of the ionizing radiation could escape.

5 Conclusions

We exploited the capabilities of the MEGARA/GTC instrument to disentangle the physical properties of different regions (down to sub-kpc scales) of four local analogs of high-z galaxies. The values obtained from different indirect indicators of LyC leakage reinforce the status of our sample as excellent reionization-era analogs, proving that the integrated properties may not fully account for the complexity of the ionizing structures. We concluded that the spatially-resolved study of a larger sample of local analogs is needed to investigate the effect of different ISM morphologies and yield statistical results that can be representative of the whole population of low-z analogs.

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