Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

Local Extreme Emission Line Galaxies as gateways to the early Universe: insights from wide galaxy surveys

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Abstract

Extreme emission line galaxies (EELGs) are crucial for understanding the most intense star formation events in the Universe and the reionization of the Universe at the Cosmic Dawn ($z>6$). While EELGs are abundant during this epoch, their faintness prevents a detailed study of their physical properties. EELGs found at lower redshifts offer a unique opportunity to investigate the physics of reionization, however a precise selection and identification of these sources is extremely challenging.

We used the J-PLUS survey, covering 3000 deg^2 of the northern sky with 12 narrow and broadband filters, to identify over 1000 EELGs at $z<0.35$. These galaxies were identified by a flux excess in narrowband filters, indicative of very large equivalent widths (>300 Å) in either [OIII]5007 or Hα, with a purity and completeness reaching $\sim$90% (considering available spectra). This approach avoids biases inherent in broadband color selections and allows the identification of fainter systems compared to spectroscopic surveys [8].

Spectroscopic follow-up observations on a subset of 50 J-PLUS candidates, supplemented by ancillary data, confirmed their EELG nature enabling the study of their physical properties through faint emission lines (Lumbreras-Calle et al. 2024 in prep). We find a remarkable similarity between low-z EELGs and JWST-detected galaxies at $z>6$, particularly in their position in the mass-metallicity diagram. Preliminary results from ancillary radio data (ALFALFA and FAST) suggest that the larger the HI gas reservoirs of the galaxies are, the stronger the starburst events.

Ongoing multiwavelength and spectroscopic studies on this sample include Chandra and OSIRIS observations, as well as accepted upcoming studies with WEAVE and HST. These efforts aim to deepen our understanding of the properties and evolutionary mechanisms of EELGs, providing valuable insights into the formation of the first galaxies and the physical state of their interstellar medium.

1 Introduction and motivation

Most galaxies in the nearby Universe show moderate to very low values of star formation rate (SFR), following a tight correlation with stellar mass. But this relationship has evolved along cosmic history, with typical galaxies at very high redshift undergoing strong star-formation events. Some of those are being discovered as extreme emission line galaxies (EELGs) at z>6 with *JWST* due to their high [OIII]5007+4959 (hereafter, [OIII]) and Hα equivalent widths (EW) (e.g. [4]), due to the emission of their HII regions. Nevertheless, they are so faint and distant that we cannot gather large samples of them to analyze in detail. To gain insight into the high-z EELG population we can study more easily their analogs at low redshift, i.e., nearby galaxies that share properties with those at the cosmic dawn: very high SFRs, compact morphologies, low metallicities, and Lyman continuum escape [6]. Our goal is to create a complete census of EELGs in the local Universe and to follow them up. We aim at understanding their properties as a statistical population, and to identify those that are the best analogs of reionization-era galaxies.

In order to do that, we need a very wide survey (since EELGs are very rare in the local Universe), it must be relatively deep (given that EELGs tend to have low masses) and we need better spectral resolution than typical broadband surveys with 5 filters, to avoid biases in the selection of objects with strong emission lines. A survey that fulfills all these criteria is the Javalambre Photometric Local Universe Survey (J-PLUS).

2 J-PLUS database and selection of EELGs

J-PLUS is a multiband survey performed from the Observatorio Astrofísico de Javalambre (OAJ) using the JAST80 80 cm telescope, with the T80Cam camera (2 deg^2 field of view, and pixel scale of 0.55 arsec pix^{-1}). The J-PLUS photometric system is composed of 12 filters, 5 broadband (similar to those of SDSS), and 7 narrow or mediumband (Fig. 1). We used data from the DR3 of J-PLUS[1] , covering almost 3000 deg^2 down to $r \sim$21.8 mag.

We have taken advantage of the J-PLUS mediumband filters to identify strong emission lines in the spectral energy distribution (SED) of the galaxies. For our first three samples, we have selected objects with excess of flux in at least one mediumband filter ($J0515$, $J0660$, or $J0861$) compared with an adjacent broadband. These selections correspond to [OIII] at redshift 0.006<z<0.055, Hα at z<0.017, and Hα at 0.28<0.34, respectively. In the case of the fourth sample, we have followed the opposite approach: selecting objects with excess of flux in the broadband *iSDSS* filter compared with the adjacent narrowbands.

This way, we obtain large samples of objects, but most of those that have SDSS spectroscopic information available are not EELGs: they are stars or AGNs. To clean the sample, we cross-match the J-PLUS objects with the *unWISE* catalog [13]. The diagram showing infrared-visible color $W1$-$rSDSS$ as a function of $rSDSS$ magnitude allows us to separate EELGs from contaminants, reaching completeness and purity values of $\sim$ 90% [8].

After removing most contaminants, we perform SED fitting on the remaining objects, to

[1]All DR3 data is available at https://www.j-plus.es/datareleases/data_release_dr3.

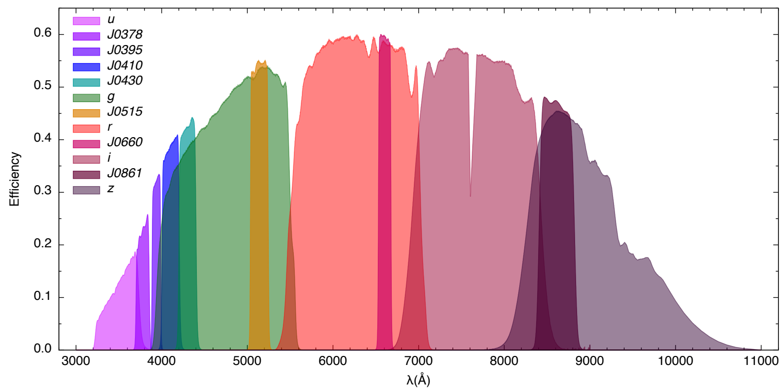

Figure 1: Transmission curves of the 12 filters used in the J-PLUS survey (from [3]).

estimate physical parameters and further refine the samples. The SED fitting was performed using `CIGALE` [1], considering nebular emission, and using a two stellar population model with rapidly exponentially declining star formation history [8] (see Fig. 2).

To select the final samples of EELGs, we use the `CIGALE` continuum emission and the flux in the filter affected by the strong emission line to estimate the EW. We made then a cut in the sample, keeping only the objects with high EW and signal-to-noise ratio above 3. These cuts were different for each filter considered, depending on their width in wavelength, and were determined studying the completeness of the objects recovered as a function of EW, using the galaxies with available spectra. For [OIII] emitters in J0515, we recovered 678 galaxies with EW$>$ 300 Å. For Hα emitters, we found 88 in J0660 with EW$>$ 200 Å, 514 in J0861 with EW$>$ 400 Å, and 736 in iSSDSS with EW$>$ 600 Å.

In total, we have compiled a sample of over 2000 EELGs in four different subsamples, with $\sim$ 80% being new identifications. The results of the analysis of the first subsample ([OIII] emitters) were presented in detail in [8]. The SED fits show very young bursts of star formation (below 6 Myr), low stellar masses (with a median value of 10^8 M$_\odot$), and little dust extinction (with E(B-V)$\sim$0.15). The results for the other samples are similar, with an expected increase in typical stellar masses for the samples at higher redshifts.

3 Spectroscopic analysis of J-PLUS EELGs

Our key goal analyzing the spectra of J-PLUS EELGs was to derive the physical properties of their interstellar gas and compare them with their high-z counterparts. We have performed several campaigns of follow-up spectroscopy on galaxies in our sample with the Isaac Newton Telescope (INT) at the Roque de los Muchachos Observatory. We used the Intermediate Dispersion Spectrograph (IDS), covering in all cases the rest-frame wavelength range from 3600 Å to 6800 Å. All 62 galaxies observed were confirmed as low redshift EELGs. We have included as well in our analysis 80 additional spectra, from the SDSS, DESI, and LAMOST surveys, measuring the EWs and fluxes with our custom made code in all surveys.

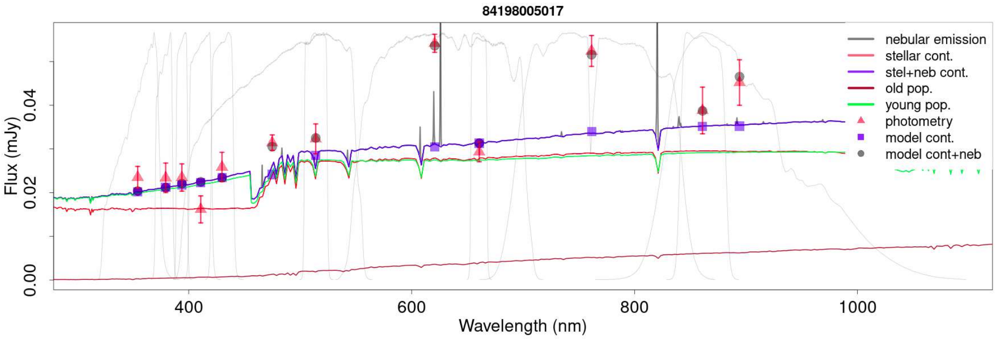

Figure 2: SED fitting using `CIGALE` on a J-PLUS EELG.

First, we determined the electronic density using the ratio between the [SII]6717/[SII]6731 lines, that resulted in most of the galaxies close or below (within uncertainties) of the low density limit (100 cm^{-3}). Then, considering this density, we have used the [OIII]4363 and [OIII]5007 emission line fluxes to determine the oxygen abundance with the direct method, calculating first the electronic temperature. We have used for all this the `Pyneb` code [9].

The results for oxygen abundance (12+$\log_{10}$(O/H)) are presented in Fig. 3, as a function of stellar mass (derived in the `CIGALE` fits on J-PLUS data). We also overplot the values for high redshift samples [11, 10], and previous studies of low redshifte EELGs [7, 14, 12]. We note that the J-PLUS sample covers densely a region of de diagram (at 12+$\log_{10}$(O/H) $\sim$ 7.6 and $\log_{10}(M_\star/M_\odot) \sim 7.9$) that was poorly covered by low-z analog samples before, but where several of the recently discovered high-z galaxies lie.

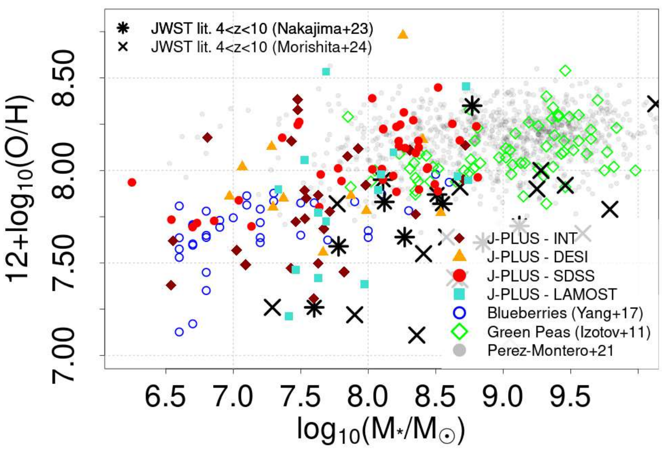

Figure 3: Oxygen abundance as a function of stellar mass, for J-PLUS EELGs, other low-z EELGs [7, 14, 12] and high-redshift EELGs detected with *JWST* [11, 10].

We have an active program at the Gran Telescopio Canarias (GTC) observing fainter galaxies than those targeted with the INT. 24 galaxies have been observed, with a much higher detection rate of the faint emission lines ([OIII]4363, [NII]6583, and [SII]6717,6731).

4 Additional follow-up and future prospects

4.1 Chandra and Hubble space telescopes

To characterize in detail the stellar populations of EELGs, we have secured X-ray observations on 7 J-PLUS EELGs using the *Chandra* observatory (P.I. J. Irwin). We intend to determine if the population of X-ray binaries in EELGs is higher than in typical star forming galaxies.

As a joint program with *Chandra*, we have requested and obtained *Hubble* Space Telescope (*HST*) observations. We intend to match potential X-ray sources to optical counterparts, but also to unveil the parsec-scale structure of the interstellar medium in local EELGs, given how close they are to us. Since they are similar to reionization-era galaxies, this analysis of local galaxies would give insights into the structure of z>6 galaxies at a resolution unattainable even with *JWST*.

The observations have targeted the UV, the Hα emission line through a narrowband filter, and the near-IR. In the four galaxies already observed, we identify complex morphologies, even if in the ground-based observations showed no features. In addition, there are clear differences in the structures between the filters, suggesting the existence of separated areas, some dominated by the underlying older populations, but also others by young bursts (in UV) and others by even mnore recent ones (Hα).

4.2 Synergies with SKA and its precursors and pathfinders

We have also cross-matched our complete sample of EELGs with available radio observations of neutral gas (HI). This will allow us to explore some of the potential triggers of the starbursts happening in EELGs, i.e., the fuel needed for the star formation. In particular, we take advantage of the good photometric redshifts we derive for the EELGs in J-PLUS to go beyond the existing catalogs of optical counterparts of radio sources. We find additional 50 EELGs in ALFALFA [5] and 79 in FASHI [15], compared to the 17 and 31, respectively, available in their catalogs of optical counterparts. Preliminary analysis of these results show that we reach very high ratios of HI mass (M_{HI}) to stellar mass. In fact, we find a very strong correlation between the ratio $M_{HI}/M_{\star}$ with the specific star formation rate, suggesting that the abundance of HI is a very important driver of the strength of the starburst in EELGs.

5 Conclusions

We have demonstrated that J-PLUS can select complete and pure samples of EELGs up to z=0.35, by identifying excesses of flux due to the Hα or [OIII] emission lines. We have compiled over 2000 EELGs, with an efficacy over 20 times higher than broadband surveys.

Follow-up spectroscopy shows that the metallicity of local J-PLUS EELGs is similar to those at z>6, covering a gap in the mass-metallicity relation of low-redshift analogs. X-ray and *HST* observations will allow us to further explore the X-ray binary population and the parsec-scale structure of the galaxies, separating the older, intermediate, and young stellar populations. Radio observations of J-PLUS EELGs will help us understand the triggers of extreme star formation events, likely related to the availability of HI.

These results will be presented in upcoming studies, paving the way to a more complete understanding of low redshift EELGs and their high redshift counterparts.

Acknowledgments

This work is based on observations made with the JAST80 telescope at the Observatorio Astrofísico de Javalambre (OAJ), in Teruel, owned, managed, and operated by the Centro de Estudios de Física del Cosmos de Aragón. We acknowledge the OAJ Data Processing and Archiving Unit (UPAD) for reducing and calibrating the OAJ data used in this work. Funding for the J-PLUS Project has been provided by the Governments of Spain and Aragón through the Fondo de Inversiones de Teruel; the Aragón Government through the Reseach Groups E96, E103, and E16_17R; the Spanish Ministry of Science, Innovation and Universities (MCIU/AEI/FEDER, UE) with grants PGC2018-097585-B-C21 and PGC2018-097585-B-C22; the Spanish Ministry of Economy and Competitiveness (MINECO) under AYA2015-66211-C2-1-P, AYA2015-66211-C2-2, AYA2012-30789, and ICTS-2009-14; and European FEDER funding (FCDD10-4E-867, FCDD13-4E-2685). The Brazilian agencies FINEP, FAPESP, and the National Observatory of Brazil have also contributed to this project. ALC and JAFO acknowledge financial support by the Spanish Ministry of Science and Innovation (MCIN/AEI/10.13039/501100011033), by "ERDF A way of making Europe" and by "European Union NextGenerationEU/PRTR" through the grants PID2021-124918NB-C44 and CNS2023-145339; MCIN and the European Union – NextGenerationEU through the Recovery and Resilience Facility project ICTS-MRR-2021-03-CEFCA.

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