A JWST Pure-Parallel Search for the First Galaxies With PANORAMIC

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Abstract

The James Webb Space Telescope offers unparalleled capabilities for observing the most distant objects in the universe, allowing us to study the first galaxies to form. In this work, the Lyman-break technique and spectral energy distribution fitting were used to analyse the JWST PANORAMIC survey and identify 26 robust galaxy candidates at redshifts greater than 9.5, including three around redshift 14.5. These candidates will make excellent targets for follow-up spectroscopy. The derived UV luminosity function at $z = 14.5$ is consistent with literature determinations at similar redshifts and implies a modest evolution in the number density of galaxies from $z \sim 14$ to $z \sim 11$. Future research based on this work could determine when the first galaxies formed, confirming or challenging current theories of cosmic evolution.

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Introduction

As light travels at a finite speed, looking further out means looking back in time. The light from the earliest-formed galaxies travels billions of light years to reach us, and in the process gets redshifted due to the expansion of the universe. Only the largest, most powerful, and technically advanced space telescope can detect them: the James Webb Space Telescope (JWST). Operating for just over two years, JWST has already revolutionised the field of astronomy as its deep infrared vision allows us to observe galaxies at extreme redshifts, such as JADES-GS-z14-0, the earliest and most distant spectroscopically confirmed galaxy known so far. At a redshift of $z = 14.32$, it was formed 290 million years after the Big Bang, likely making it one of the very first galaxies to form (Carniani *et al.* 2024). Studying this and other similar galaxies gives invaluable insight into the formation and evolution of galaxies and the whole universe.

While the method involved in this study (photometry) requires analysing only a small part of the galaxy's spectrum of light, spectroscopy demands the time-consuming process of taking its explicit spectrum and comparing emission lines of various elements to laboratory experiments. Photometry is widely used to quickly select galaxy candidates for a spectroscopic confirmation of their redshifts. The large amounts of data released by the JWST until now led to discoveries of many high-redshift ($z > 9.5$) galaxy candidates (e.g., Bouwens *et al.* 2023; Harikane *et al.* 2023a) and spectroscopic confirmation of some of them (Harikane *et al.* 2023b; Castellano *et al.* 2024). Nevertheless, so far, there are only around 30 spectroscopically confirmed galaxies at redshifts greater than 9.5 in total (Harikane *et al.* 2024), making the predictions about the early universe highly uncertain. More data is necessary to better understand the initial conditions of galaxy evolution and place constraints on the period in the history of the universe when they began forming. Therefore, the main motivation for this project is expanding the sample of high-redshift ($z > 9.5$) galaxies for robust statistical analysis. Such analysis often involves measuring the UV luminosity function, which quantifies the abundance of galaxies as a function of the magnitude in the UV part of the spectrum (M_{UV}). Luminosity-weighted integral of the UV luminosity function gives the UV luminosity density, which can be converted to the star formation rate density (star formation rate per unit comoving volume). This can be later compared to various models of galaxy evolution to investigate whether our understanding of how galaxies evolved in the early universe is backed up by observations. The time frame of this study only allowed us to calculate the UV luminosity function at a redshift of $z = 14.5$, leaving the remainder of the analysis for future work.

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One of the most effective and common methods to select high-redshift galaxies is the Lyman-break technique (e.g., McLeod *et al.* 2023). It relies on the fact that radiation at wavelengths shorter than the Lyman limit at 1216 Å is almost completely absorbed by the intergalactic medium (Dunlop 2012). Due to cosmological redshift, this limit is moved to longer wavelengths for galaxies far away from us. By using images taken with two different filters, one above the limit and one below, a Lyman-break galaxy can be discovered since it will only be detected in one of the images. This specific feature allows us to quickly select interesting candidates from large galaxy samples for more time-consuming spectroscopic confirmation.

To further reduce the sample size and only include the most likely candidates, spectral energy distribution (SED) fitting can be implemented. The SED is a plot of how the energy emitted by an object varies as a function of wavelength. The SED of a galaxy depends on various physical properties, such as redshift, age, stellar mass and dust extinction (Conroy 2013). SED fitting comes down to comparing the observed SEDs of individual galaxies to thousands of simulated templates based on various models and selecting the solution that provides the best match to observations. The most robust candidates will have a strong match with one high-redshift solution and a weak match with all low-redshift solutions (Pacifici *et al.* 2023).

The PANORAMIC survey (Williams *et al.* 2024) used in this analysis consists of 40 uncorrelated NIRCam (Near Infrared Camera) pointings, each of them utilising the F115W, F150W, F200W, F277W filters and at least two of the following: F356W, F410M and F444W. Each filter is centred at a different wavelength, for example, F115W is centred around 1.15 micrometres. Their transmission curves and other relevant information can be found at JWST (2017). Each pointing covers an area of about 10 square arcminutes, giving a total area of 0.1 square degree, making this study one of the largest JWST-based searches for high-redshift galaxies to date.

Methods

Firstly, the positions of light sources in all images of the survey were determined and their aperture photometry (flux measurement) performed with SourceExtractor (Bertin *et al.* 1996) in a 0.3" diameter aperture. SourceExtractor, run in dual mode, allows for the detection of objects in one image and their flux measurements in another. The F200W filter images were used for object detection as the spectrum of a high-redshift galaxy is expected to peak around the wavelength covered by this filter. The constructed multiwavelength photometry catalogues were cut to include only those objects that were bright in the F200W filter (with a signal-to-noise ratio, SNR, greater than 5) but were not visible in F115W (SNR $\leq$ 2). This is because for a Lyman-break galaxy at $z = 9.5$, the limit is expected to be observed at 1.28 micrometres, and the F115W filter lies just below this wavelength. An additional detection in any filter at wavelengths longer than the detection filter was introduced as a further criterion to rule out interlopers (objects that are definitively not high-redshift galaxies), such as snowballs (data artefacts caused by large cosmic ray impacts), which would typically appear in only one filter (Regan 2024).

The resulting catalogues were then input into LePHARE (Arnouts *et al.* 2011), a piece of software used for SED fitting. First, it produced spectral libraries with millions of simulated SEDs of galaxies with varying redshift, age, dust extinction etc., and later compared these to every object in each catalogue, looking for a best-fitting and second-best fitting solution. Further cuts were applied to the output catalogues to only leave galaxies that had a good-fitting high-redshift ($z > 9.5$) primary solution and a much less probable secondary solution. Besides the redshift, LePHARE also calculated the magnitude in the UV part of the spectrum which was then used to plot the UV luminosity function that was calculated following the method in Donnan *et al.* (2023).

Finally, the remaining galaxies were visually inspected to remove any that were positioned too close to the edge of an image to give reliable SNR calculations, were found to be artefacts, or did not appear to be a galaxy but rather a part of a foreground object.

Results and Discussion

Aperture photometry, SED fitting, and visual inspection led to the identification of 26 robust galaxy candidates at redshifts greater than $z = 9.5$, including three around redshift 14.5 (meaning the universe was at $\sim 2\%$ of its current age when they emitted the light we observe now):

1. PAN+53.17489-27.94433 at $z = 14.7$ — a very bright and compact object that, while the high-redshift solution is heavily favoured over any low-redshift solution, may be a dwarf star interloper. Future plans are to verify whether it is a star by fitting the photometry with stellar SED templates.

2. PAN+334.25047+0.37907 at $z = 14.5$ — even brighter than the previous candidate, meaning that it can be confirmed with single object spectroscopy as it requires as little as 4-5 hours of observation time. It is extended so a star interloper can be ruled out. After consulting the Mikulski Archive for Space Telescopes*, it has been found to lie in close proximity to the SSA22 protocluster at $z = 3.09$. While a $z = 3$ solution is heavily disfavoured by the SED fit, we cannot definitively rule out the possibility it is a faint member of this protocluster without spectroscopy. Nonetheless, such discovery would still be interesting, as a similar case occurred with the CEERS-93316 galaxy, initially predicted to be at a redshift of $z = 16.4$ (Donnan *et al.* 2023), but later revealed via spectroscopy to have a redshift of $z = 4.9$ (Arrabal Haro *et al.* 2023).

3. PAN+26.09351+17.25871 at $z = 13.4$ — a rather faint object that, fortunately, lies in an image where two more candidates were detected, allowing them to be treated with multi-object spectroscopy.

The brightest of these galaxies will be included in JWST Cycle 4 proposal (observations between July 2025 and June 2026) to confirm its redshift spectroscopically with NIRSpec (Near-Infrared Spectrograph). If confirmed, it might become one of the most distant objects ever known as the current record for the most faraway spectroscopically confirmed galaxy stands at a redshift of $z = 14.32$.

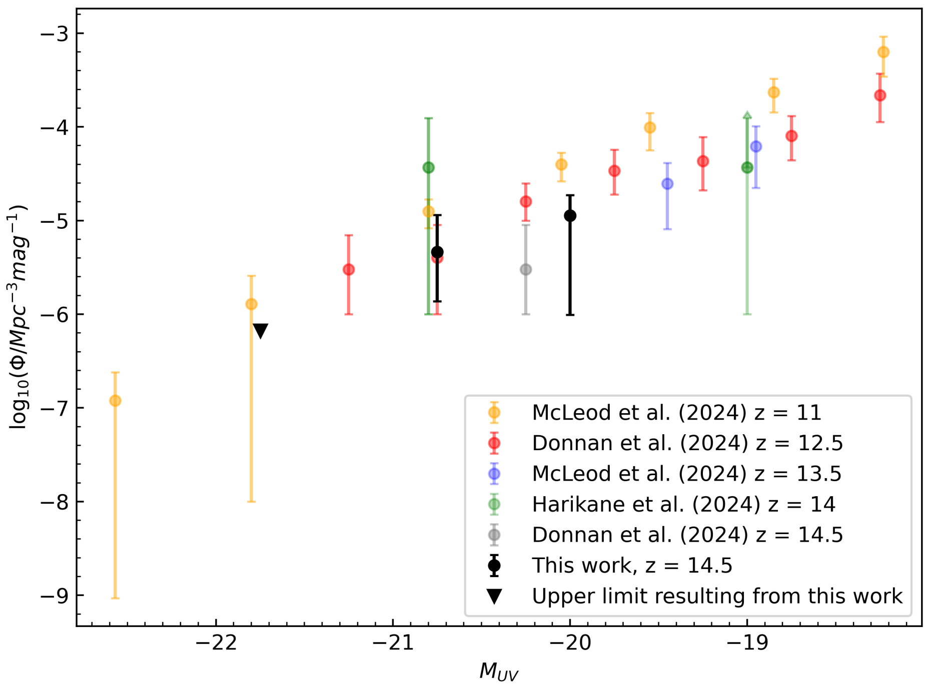

Figure 1: The evolving UV luminosity function at $z \geq 11$ including the three highest-redshift galaxy candidates found in this study binned according to UV magnitude (black points). The downward arrow indicates an upper limit — as no $z \sim 14.5$ galaxies were found with magnitudes smaller than -21.75, this signifies that their number density is smaller than 1 galaxy per the comoving volume encompassed by the whole survey. These results are consistent with previous literature at similar redshifts (McLeod *et al.* 2023; Donnan *et al.* 2024; Harikane *et al.* 2024).

The UV luminosity function (the number density of galaxies per unit comoving volume per unit magnitude, Φ, as a function of the magnitude in the UV part of the spectrum, M_{UV}) including these three galaxies is presented in Figure 1. The results are in agreement with literature at similar redshifts and

*Can be found at https://archive.stsci.edu suggest a mild evolution in the UV luminosity function from $z = 14$ to $z = 11$. Data points corresponding to different redshifts appear to lie near a single line, indicating that the luminosity function remains relatively constant over time.

Secondary solutions produced by LePHARE typically corresponded to low-redshift galaxies with very high reddening due to dust, or extreme emission lines. While many interlopers were removed in the SED fitting process, the only way to definitively confirm our candidates is through spectroscopy. Other possible interlopers are dwarf stars, whose spectral features may imitate a Lyman break. Setting LePHARE to compare the observed photometry to stellar libraries could eliminate some of these, but this approach will require newer, updated stellar libraries with sufficient wavelength coverage to match the JWST NIRCam observations, which extend to ~ 5 micrometres. This work is planned to be done in the future.

Conclusions

In summary, photometric methods such as Lyman-break selection and SED fitting were implemented to search an area of roughly 0.1 square degree for high-redshift galaxy candidates, identifying 26, including three at $z = 14.5$. The spectrum of the most robust and bright candidate will be taken in the future to confirm its redshift. The calculated UV luminosity function at $z = 14.5$ aligns with previous studies and exhibits a moderate evolution between $z = 14.5$ and $z = 11$. This function can later be used to calculate the UV luminosity density and star formation rate density, helping us to test and refine galaxy evolution models and gain a better understanding of the cosmic history.

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