Peering into the Cosmic Dawn: JWST Cycle 1 Data Reveals Early Galaxy Candidates at Redshifts z > 9.5

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Abstract

Observing high-redshift objects provides a window into the past, enabling insight into galaxy formation, matter distribution, and the nature of dark matter and energy. This report presents a sample of work on Cycle 1 of the James Webb Space Telescope concerning the discovery of high-redshift early galaxy candidates. Potential objects from these surveys had their photometric redshift computed using the LePhare simulation program and analysed using LePhare-generated spectral energy distribution fits. A total of 46 candidates at redshifts beyond $z > 9.5$ were found between three surveys: two in DDT2750, 30 in JADES, and 14 in NGDEEP.

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Introduction

The search for high-redshift galaxies comes from a desire to know more about the early universe; these galaxies appear now as they were in the past. Their structure, metallicity, and dynamics can give insight into how galaxy formation and evolution has changed with time. The development of better instruments and further constraint of cosmological constants has led to redshift determination of sources further and further back in time.

Due to the high number of foreground interlopers, the techniques used to select only high-redshift galaxies need to be specific. One of the most effective is the selection of galaxies via the Lyman break – a distinct "step" in the blue side of the spectrum, where the majority of ultraviolet (UV) light from young stars has been absorbed by neutral interstellar hydrogen gas (Dunlop 2013). With the combined effect of the Lyman-α forest at higher redshifts (from Lyman-α absorption at $\lambda_{rest} = 1216$Å), the optical thickness becomes so great that only a sharp-edged "step" in the spectrum remains.

It is possible to select high-redshift galaxies by viewing candidate objects through different filters and seeing in which one an object "drops out" – the object should be repeatedly visible in all longer wavelengths, but no longer so at the bluest wavelengths. The filter in which the object "disappears" will correlate to the redshift at which it lies, as it will relate to how much the Lyman break has been shifted along with the spectrum. This technique has successfully been utilised on early-release James Webb Space Telescope (JWST) data, resulting in a multitude of high-probability candidates (Donnan *et al.* 2022; Harikane *et al.* 2023). Given this result, the same technique was utilised in this project.

The JWST data for this report was taken from three separate surveys – DDT2750, JADES, and NGDEEP – with each survey focused on a different area of the sky, and utilising a different filter set for observations. JADES in particular was highly anticipated; instruments used as part of this survey allowed an unprecedented extension of imaging into the infrared spectrum. JADES was the largest survey included in this report, lying in the footprints of the Hubble Deep Field and the Hubble Ultra Deep Field (JADES 2023). All filters used as part of this project can be found in the JWST and Hubble Space Telescope User Documentation (HST 2020; JWST 2023). The filters used for each survey were different and had different wavelength overlap regions†.

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†DDT2750 utilised filters F115w, F150w, F200w, F277w, F356w, F444w. JADES utilised F435w, F606w, F814w, F090w, F115w, F150w, F200w, F277w, F356w, F410m, F444w. NGDEEP used F435w, F606w, F814w, F115w, F150w,

Methods

Catalogues

SourceExtractor is a command-line program which analyses large-scale astronomical files and is able to reduce and compile catalogues of potential sources from said data (Bertin *et al.* 1996). By running SourceExtractor in dual image mode, it was possible to make detections in one image and use those object coordinates to make measurements in a second image. Hence, the F277w filter image was used as the detection image for each dataset, allowing for the creation of catalogues. This specific filter was chosen as it was well-populated across all three surveys.

Each catalogue contained the object identification number, coordinates, object flux, and flux error; these separate filter catalogues were assembled into one master catalogue per survey. The compiled catalogues were cut to select for desired objects – only those detected at 5σ over the noise in F277w would be selected, and were subjected to a secondary non-detection cut in F115w and F090w as a final step. These cuts ensured that the objects that remained in the catalogues statistically fulfilled the criteria for detection.

These reduced catalogues could then be input into the LePhare program. LePhare is a set of Fortran commands that compute an object's photometric redshift and perform spectral energy distribution (SED) fitting on datasets, using galactic models from its libraries (Arnouts *et al.* 2011). The LePhare output totalled thousands of objects and had to be sorted for the desired outcome. Objects were selected between redshifts of $9.5 < z < 16$; any higher than 16 was anticipated to be noise. Objects were then cut at the statistical hypothesis value of $\chi^2 < 50$.

Even after this selection, the number of total objects remained very high. It was improbable that so many high redshift galaxies would be present – more likely that some of the candidates were false positives. A more selective cut was performed in F277w, seeking any objects 8σ above the noise in comparison to the 5σ selection chosen before. These catalogue cuts yielded a manageable sample of objects that could be visually assessed to select high-redshift candidates via the postage stamp method.

Postage Stamps

A reduced catalogue with just the high-redshift objects was created for each survey, containing the object coordinates in each image. From this, individual "stamps" were made by centering the identified object in each image cutout for each filter.

High-redshift, star-forming objects such as early galaxies were expected to only be visible at longer wavelengths due to the Lyman break. As different filters cover a different waveband, only certain wavelengths of light can be seen in each image; the filter in which the object "drops out" correlates to the expected redshift value. An example of a successful object detection can be seen in the "post-stamp" set in Figure 1. Any "post-stamp" set with this dropout criteria had the object number noted down, and these chosen objects were re-run through LePhare to obtain primary and secondary SED fits.

Results and Discussion

The primary solution created by LePhare simulated a spectrum of a high-redshift galaxy projected at the same redshift as the solution found for the object. The secondary solution posited a galaxy at a much lower redshift but with a very red ('dusty') spectrum to make it appear more redshifted. The object's magnitude and wavelength values could be compared for reference.

For many of the objects, there was no secondary solution in the initial run – a sign of a very good primary fit, or that LePhare did not project a secondary fit. To gain a secondary low-redshift fit to compare the primary solution to, a second run of objects was input into LePhare with changed solution parameters to force a low-redshift outcome. From analysis by eye of the postage stamps and subsequent comparison to SED fits drawn up of the object, a total of two candidate objects were found in the DDT2750 survey, 30 in JADES, and 14 in NGDEEP. All these are projected to lie at redshifts beyond $z = 9.5$.

The next step for this research would be to look at the UV luminosity density and the Star Formation Rate Densities of these galaxies. These sorts of results can be added to and compared to previous studies

F200w, F277w, F356w, F444w. Filters F606w, F814w are from ancillary HST surveys (Baggett *et al.* 2006; HST 2020).

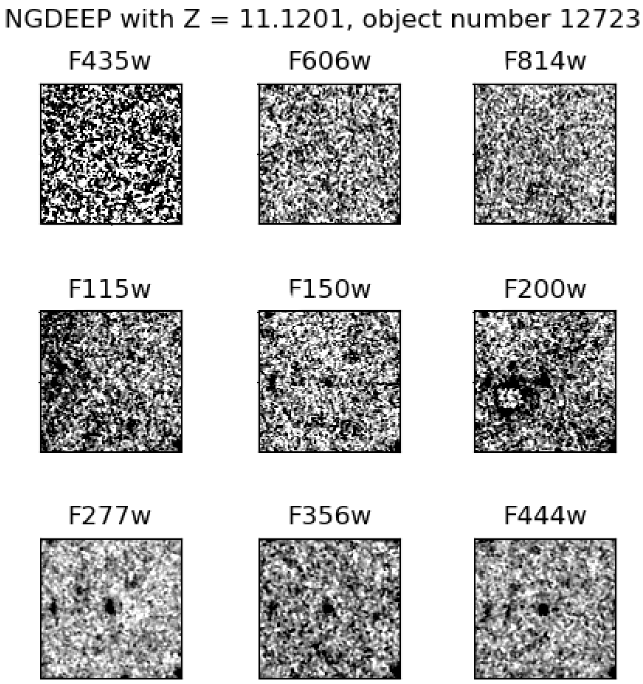

Figure 1: Cutouts of the NGDEEP object 12723. The object is visible as a black dot at centre of each image cutout in filters used at longer wavelengths (F150w-F444w), while disappearing from shorter-wavelength observations (F435w-F115w) due to the Lyman break. This demonstrates the criteria necessary to visually identify a potential high-redshift candidate by the method of "postage stamps".

to further support or disprove existing relations, and ultimately yield a better picture of the early universe (Donnan *et al.* 2022).

For a first foray into the high-redshift regime, this project served as a good introduction to the processes involved in handling high-redshift data. The results suggest the existence of candidates at z-values much higher than records set prior to the launch of the JWST (Oesch *et al.* 2016; Jiang *et al.* 2020). If confirmed spectroscopically, these candidates could very well be some of the first galaxies formed in our universe.

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