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Barred galaxies beyond cosmic noon: a first JWST glance

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Abstract

Stellar bars represent a key observable related to the dynamical evolution of disk galaxies across cosmic time, from low to the highest redshift. However, detailed morphological studies beyond $z = 1$ were mostly limited by the spatial resolution of available observations. In this work, we described an observational study of the bar population beyond cosmic noon, which was possible only thanks to the extraordinary capability of the NIRCam instrument onboard the James Webb Space Telescope (JWST). We derived the bar fraction at $3 < z < 4$ from a visual inspection of a sample of 110 galaxies in the GOODS-S cosmological field, using the public dataset from the JWST Advanced Deep Extragalactic Survey (JADES). NIRCam bands F200W and F444W were used in the morphological classification by independent visual inspection of different collaborators. For those sources classified as strong barred galaxy candidates, the ellipse fitting method was then employed to confirm the bar presence. Furthermore, we derived the 2D Sérsic profiles and the non-parametric morphological parameters of these galaxies. We identified five disk galaxies that could be classified as barred based on their morphology observed at 4.4 μm. Among these, two galaxies were confirmed as barred at both shorter (F200W) and longer wavelengths (F444W). If further complementary morphological analyses support these findings, galaxies ID 155468 ($z_{\rm spec} = 3.19$) and ID 210751 ($z_{\rm spec} = 3.42$) may be the highest-redshift barred galaxies detected to date.

1 Introduction

The formation and evolution of galaxies are driven by complex interactions between stars, gas, dust, and dark matter. Understanding the structure of galaxies is essential for diagnosing their transformations across cosmic time. Early morphological studies, such as Hubble's tuning fork, laid the groundwork for classifying galaxies, with the Hubble Space Telescope (HST) enabling observations up to redshift $z \sim 1-2$ [15, 8, 2, 3]. The James Webb Space Telescope (JWST) has extended this range, showing that disk galaxies dominate even at high redshifts ($z \sim 8$), suggesting an earlier formation of the Hubble Sequence than previously believed [11, 9, 5].

Locally, large surveys like the Sloan Digital Sky Survey (SDSS) [16] have revealed that $30-45\%$ of nearby disk galaxies have strong bars, a fraction that increases to $60-70\%$ in the near-infrared [1]. Bars play a critical role in galaxy evolution by redistributing angular momentum and driving processes such as central star formation and bulge growth [12]. Although earlier HST studies indicated a decline in bar presence at higher redshifts, recent JWST findings suggest that previous estimates might have been limited by resolution, with barred galaxies now detected up to $z \sim 3$ [4, 13, 7].

In this context, this work aims to look for the population of first stellar bars forming in high-redshift disk galaxies, in the range $3 < z < 4$ (lookback time beyond 11 Gyrs), using public data obtained with the NIRCam instrument mounted on the JWST telescope. The code developed for this work is available in GitHub at https://github.com/leoarriscado/TFM.

2 Data and sample

This study uses data from the second data release (DR2) of the JWST Advanced Deep Extragalactic Survey [6][1], which encompasses part of the GOODS-South cosmological field. The photometric data employed were obtained using the F200W and F444W filters of the NIRCam instrument on the JWST.

For the sample selection, galaxies were chosen based on their properties at 2 and 4.4 μm (i.e., F200W and F444W). Initially, all galaxies with photometric redshift in the range $3 < z < 4$ were selected, resulting in a sample of 9334 galaxies. A magnitude cut was then applied, selecting only sources with $m_{AB} < 25$ mag in both F200W and F444W filters. This ensured the selection of sufficiently bright (high signal-to-noise ratio) and spatially resolved galaxies, suitable for morphological characterization. After applying these criteria, our final sample is composed of 110 galaxies.

3 Methodology

This section outlines the three methods used to classify the galaxies in our sample by morphology, focusing on identifying those with stellar bars. These methods are:

[1] All the data used in this work is publicly available at https://archive.stsci.edu/hlsp/jades.

1. Visual classification of the sample of 110 galaxies by three independent collaborators.

2. Ellipse fitting of the surface-brightness distribution of the best barred galaxy candidates.

3. Analysis of the parametric and non-parametric morphology of the best barred galaxy candidates.

Cutouts were created for each galaxy from the sky-subtracted JADES DR2 mosaic images in various filters. The initial step involved a visual classification of the sample's morphology, primarily using images in the F444W band. Three independent collaborators classified the morphology of each galaxy as disky, elliptical, or irregular. Artifacts and unresolved structures were excluded, and only galaxies with an extended disk component were further inspected for the presence of a stellar bar.

Seven galaxies were identified as barred by all collaborators and were designated as the best candidates for further analysis. To identify the presence of a stellar bar, the light distribution in the F200W and F444W bands was examined, following diagnostic criteria from [10] and [14]. A galaxy was considered barred if the central ellipticity ($e_{\max} > 0.25$) remained constant within 20° of the position angle (PA). This constancy in PA suggests the presence of a coherent bar structure. In contrast, in the outer region, where the stellar disk becomes dominant, the analysis looked for a noticeable drop in ellipticity by at least 0.1 from $e_{\max}$, along with a shift in the PA of at least 10° from the average PA of the bar. This variation indicates a transition from the bar to the disk, thus confirming the presence of a bar structure extending through the central part of the galaxy. The `Photutils` package was used to model the light distribution, while the `statmorph` package provided both parametric and non-parametric morphological diagnostics, including Gini-M_{20} and CAS statistics, as well as modeling with a Sérsic profile.

4 Results and discussion

4.1 Fraction of barred galaxies at $3 < z < 4$

From visual inspection of the galaxy images, we classified them into four morphological types: elliptical, disk, irregular, and unresolved. As shown in Fig. 1, these categories represent 13.6%, 36.4%, 20.9%, and 25.5% of our sample, respectively, with 3.6% classified as uncertain. We found that 75% of disk galaxies were identified as barred by at least one collaborator, a fraction comparable to studies in the local Universe showing $50 - 70\%$ barred disks [14]. However, considering only the best candidates, the bar fraction is 17.5%, consistent with recent findings of $7 - 19\%$ up to $z = 3$ [13]. Spectroscopic data from JADES confirmed the high-redshift nature of three of our seven barred candidates, supporting the accuracy of photometric estimates.

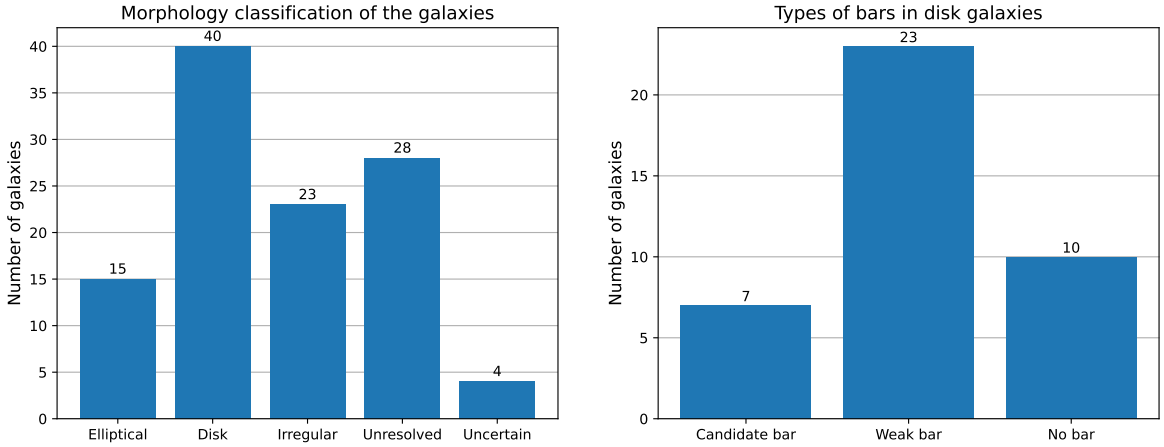

Figure 1: Results of the visual classification on our sample of 110 galaxies at $3 < z < 4$. *Left panel*: Fraction of different morphological types as classified by three independent collaborators. "Uncertain" refers to galaxies that were classified differently by each collaborator. *Right panel*: Distribution of bars in disk galaxies. Figure extracted from Arriscado 2024, M.Sc Thesis.

4.2 Morphological properties of the best barred galaxy candidates

In this section, we show, as an example, the morphological properties determined for one of our seven barred galaxy candidates, ID 210751. Fig. 2 displays the radial profiles of e and PA from the ellipse fitting. Based on the criteria detailed in Sect. 3, this galaxy was classified as a barred galaxy.

Finally, Fig. 3 presents the diagnostics obtained using `statmorph`, as outlined in Sect. 3, for the barred galaxy candidate ID 210751. The results obtained for our seven strong candidates, clearly indicate that a single Sérsic component is insufficient to accurately model the morphology of our galaxies (e.g., ID 210751), corroborating the findings from the ellipse fitting analysis.

5 Summary and conclusions

In this study, we analyzed the bar fraction distribution of disk galaxies at redshift $3 < z < 4$ using imaging data from the JADES survey captured by the JWST NIRCam instrument. We visually classified 110 galaxies brighter than 25 mag (F200W and F444W) and identified seven galaxies as strong candidates for hosting stellar bars. Further analysis of their radial profiles confirmed the presence of bars in five of these galaxies. Our findings underscore that disk galaxies are the dominant type at this redshift range, supporting recent studies. Notably, two galaxies (ID 155468 and ID 210751) are targeted for future observations to verify their status as the highest-redshift barred galaxies observed. Future studies will expand our analysis through non-parametric morphology studies, Fourier decomposition of surface brightness,

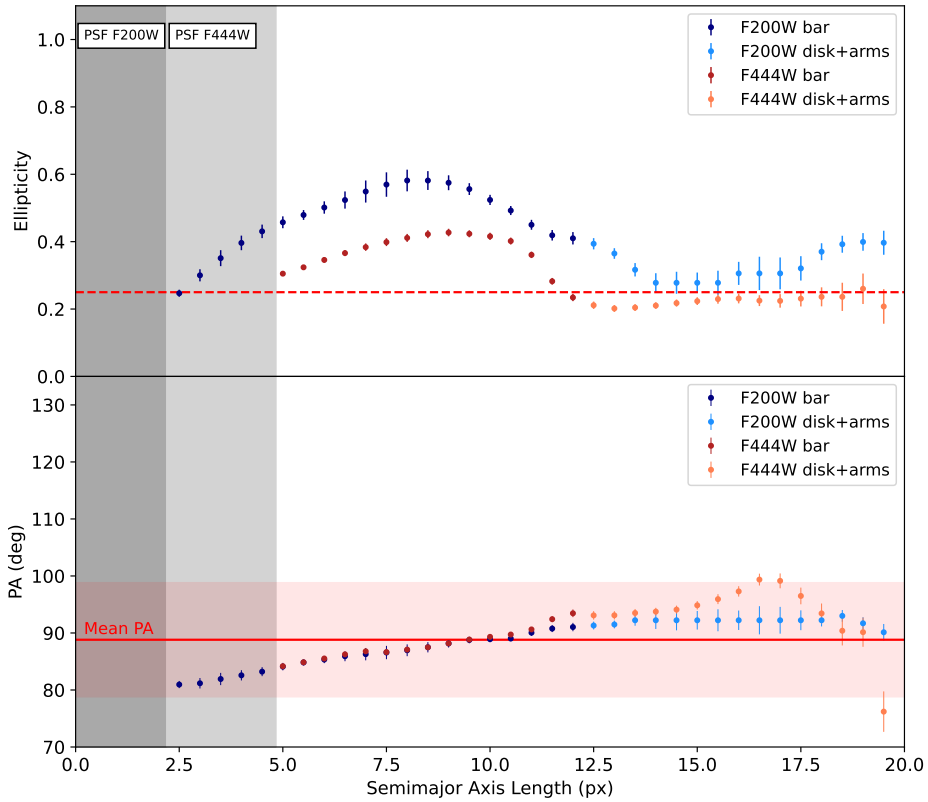

Figure 2: Radial profiles of e (top panel) and PA (bottom panel) vs semimajor axis derived from the ellipse fit, for the example galaxy ID 210751. Blue and red points stand for the profiles derived in the F200W and F444W bands, respectively. Dark points stand for the region visually identified with the bar, while light points stand for the region visually identified with the disk of the galaxy. Shaded gray regions mark the PSF FWHM in different bands. The minimum ellipticity ($e_{\rm min} = 0.25$) criterium described in Sect. 3 is shown as a red dashed line (top panel). The mean PA of the galaxy is shown as a red solid line (bottom panel), while a red shaded region marks ΔPA $= \pm 10°$. Figure extracted from Arriscado 2024, M.Sc Thesis.

and new observational data. Additionally, a larger classification effort using Zooniverse[2] will help build more robust visual datasets for galaxies at $2 < z < 4$.

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[2]The project can be visualized at the following link: https://www.zooniverse.org/projects/leoarris/galaxy-classification-with-the-james-webb-space-telescope.

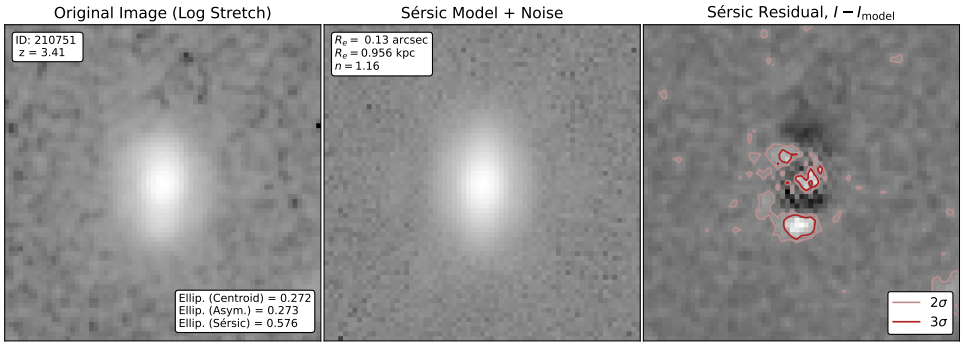

Figure 3: Example of the morphological parameters derived with `statmorph` for galaxy ID 210751 in the F444W filter. The original image oriented with North up and East left (left), the Sérsic model with Gaussian noise (middle), and the Sérsic residuals with 2σ (light red) and 3σ contours (dark red) (right). The cutouts are 67×67 pixels^2, which corresponds to 2×2 arcsec^2 (15.1×15.1 kpc^2 at $z = 3.41$). Figure adapted from Arriscado 2024, M.Sc Thesis.

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