MODERN ASTRONOMY: FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Decomposition of distant galaxies with spiral arms

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Abstract. We perform the photometric decomposition, including spiral arms, of 159 galaxies at $0.1 \le z \le 3.3$ imaged by HST and JWST in optical and near-infrared in rest-frame. We measure various properties of spiral structure and, in particular, we confirm that pitch angles increase and azimuthal length decrease with increasing z, implying that spiral structure becomes more wound with time. We also measure band-shifting effects, or the spiral-to-total ratio and width relative to the disc exponential scale, and find that band-shifting effects can be as significant, or even stronger than, evolutionary effects. Furthermore, the spiral structure becomes more asymmetric at higher redshifts.

Keywords: galaxies: high-redshift, spiral, evolution

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1 Introduction

The majority of luminous galaxies in the local Universe have spiral structures. Questions about the origin and evolution of spiral arms in galaxies are still unresolved, and observational evidence is needed to test various theories that aim to answer these questions. There are a significant number of studies devoted to the spiral structure in local galaxies (see discussion and references in Sellwood & Masters 2022). Spiral galaxies are still abundant at high redshifts, and the fraction of spiral galaxies is expected to remain significant at least up to $z \approx 4$, but systematic works concerned specifically with the spiral structure of distant galaxies are scarce and usually concern only a limited set of parameters.

Photometric decomposition is a powerful tool for examining the properties of galaxy components, including potentially spiral arms. The key idea of decomposition is to model the distribution of light in a galaxy as the sum of several components, each described by an analytical model. Nowadays, most decompositions ignore the spiral arms, mostly because of complex structure of these features. However, some papers do model the spiral arms. For example, the `GALFIT` photometric decomposition package (Peng et al. 2010) allows one to model various non-axisymmetric features, including spirals, with Fourier and bending modes, and this approach has been used in different works. In our previous works (Chugunov et al. 2024; Marchuk et al. 2024) we have developed our own model of spiral arms and utilized it to perform the decomposition of local galaxies, showing the viability of this method.

2 Data and methods

2.1 Images

To study spiral structure in distant galaxies, we utilize data from the COSMOS survey of HST (Koekemoer et al. 2007) and from two surveys of JWST, namely CEERS (Bagley et al. 2023) and JADES (Rieke et al. 2023). The depth and high resolution of these images allow one to observe the structure of distant galaxies, including their spiral arms, and for our further analysis we select images of galaxies with recognizable spiral structure. Our final sample consists of 159 spiral galaxies at redshifts $0.1 \leq z \leq 3.3$ in 329 individual images. Of this sample, 126 galaxies are taken from the HST COSMOS survey at $0.10 \leq z \leq 1.02$, while the JWST CEERS and JADES surveys are the source for the remaining 33 objects at $1.05 \leq z \leq 3.30$. For these 33 objects, multiwavelength data are available in several filters, and we have analyzed 203 images of them in different wavelengths. Taking into account the redshift, the rest-frame wavelengths are located from the blue to the near-infrared parts of the spectrum. For the COSMOS sample, we used only a single near-infrared filter.

2.2 Spiral arms model

To model the 2D light distribution in spiral arms, we use a function with 21 parameters for each arm, taken from our previous work, with small, mostly technical changes (see Section 3 in Chugunov et al. 2024). The most complete description of the model and the changes from the version used in the previous work can be found at https://github.com/IVChugunov/IMFIT_spirals.

We briefly remind that our model is capable to produce each single spiral arm with different pitch angle, which can vary as 3rd degree polynomial of azimuthal angle. The distribution of light along the arm is mostly exponential with radius, since spiral arms are part of a disk, but with a truncation near the beginning and end. The distribution of light along the arm can be asymmetric, is described by the Sérsic function, and the width can be variable.

2.3 Decomposition

To perform the photometric decomposition of the images, we use the `IMFIT` package (Erwin 2015), which we have modified to implement our spiral function (available at https://github.com/IVChugunov/IMFIT_spirals). For each galaxy, we use a model with a few appropriate components, which usually including a disk and bulge, and a bar if necessary, as well as an appropriate number of spiral arms. Fig. 1 shows an example of our decomposition model.

3 Results

We have measured a large number of parameters using photometric decomposition. Tables with these results are available at https://github.com/IVChugunov/Distant_spirals_decomposition.

3.1 Dependence on lookback time

First, we will focus on the parameters of the spiral arms that depend on the redshift z or, equivalently, on the lookback time t_L. The pitch angle μ and the azimuthal length l_ψ (i.e., the angle between the beginning and end of the spiral arm with respect to the center) are the most notable of these. (Since different arms have different parameters, we consider the weighted average by luminosity over all spiral arms in a galaxy). The average value of μ over the sample is 16.0 deg, and for l_ψ it is 244 deg. The dependence

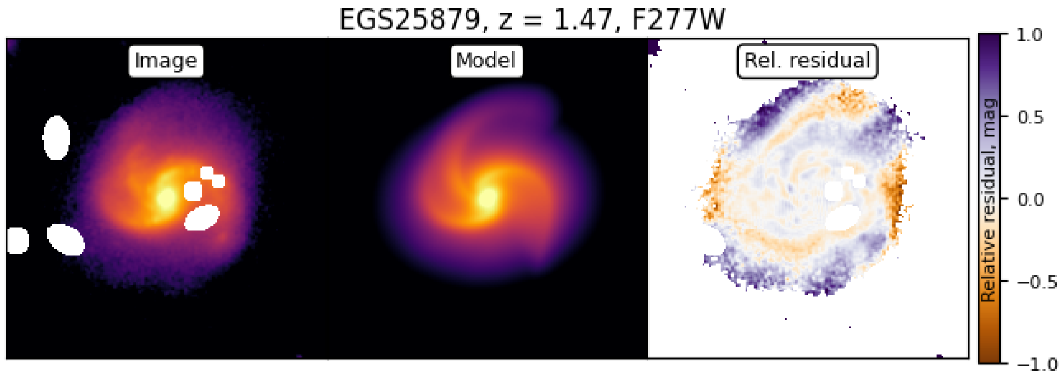

Fig. 1. Decomposition example of one of the galaxies in the sample. From left to right: image, model with spiral arms, relative residual (with a corresponding color bar on the right: pixels where the image flux is underestimated by the model are in purple, and where it is overestimated are in orange).

of these two parameters on t_L is shown in Fig. 2. The pitch angle clearly increases with t_L at a rate of 0.5 deg/Gyr, implying a decrease as we get closer to the modern epoch. Length decreases with larger t_L by 7 deg/Gyr. Taking together, these trends imply that the spiral arms have become more wound with time.

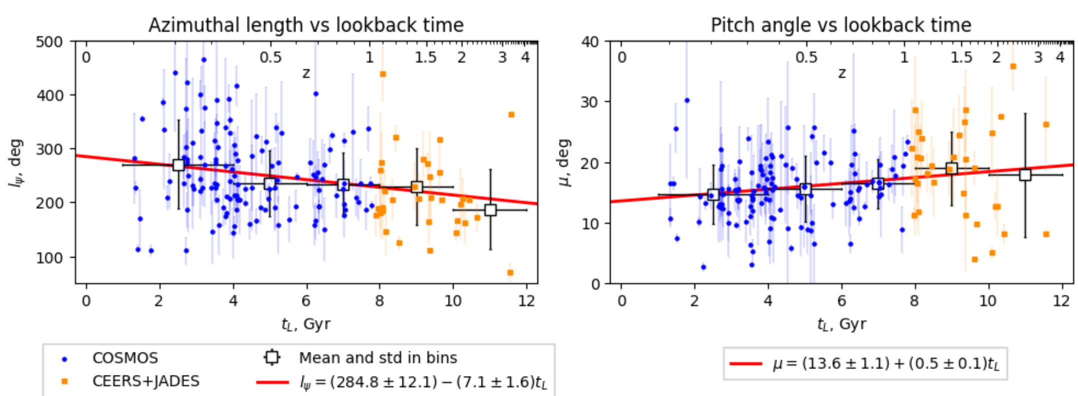

Fig. 2. Dependence of azimuthal length l_ψ (left) and pitch angle μ on lookback time t_L. The linear approximation is shown for the full sample, as well as for some subsamples.

3.2 Dependence on rest-frame wavelength

Since a fraction of the galaxies in our sample have multiwavelength data available, we can examine the dependence of different parameters of the spiral pattern on wavelength. Redshift means that images in a single filter of galaxies at different z capture the different rest-frame wavelength, and one needs to distinguish evolutionary effects from band-shifting effects. To do this, we perform a bilinear fit of several parameters as a function of the lookback time t_L and rest-frame wavelength $\lambda_{\rm rf}$, and show the results in Fig. 3. Most importantly, we observe that the relative width of the spiral arms w/h (which is the spiral arm width w normalized to the disk exponential scale h) strongly depends on $\lambda_{\rm rf}$, with w/h increasing by 0.37 per 1 μm of wavelength in the optical and near-infrared. This dependence affects the observed width even more than any evolutionary effects, and is probably related to the different

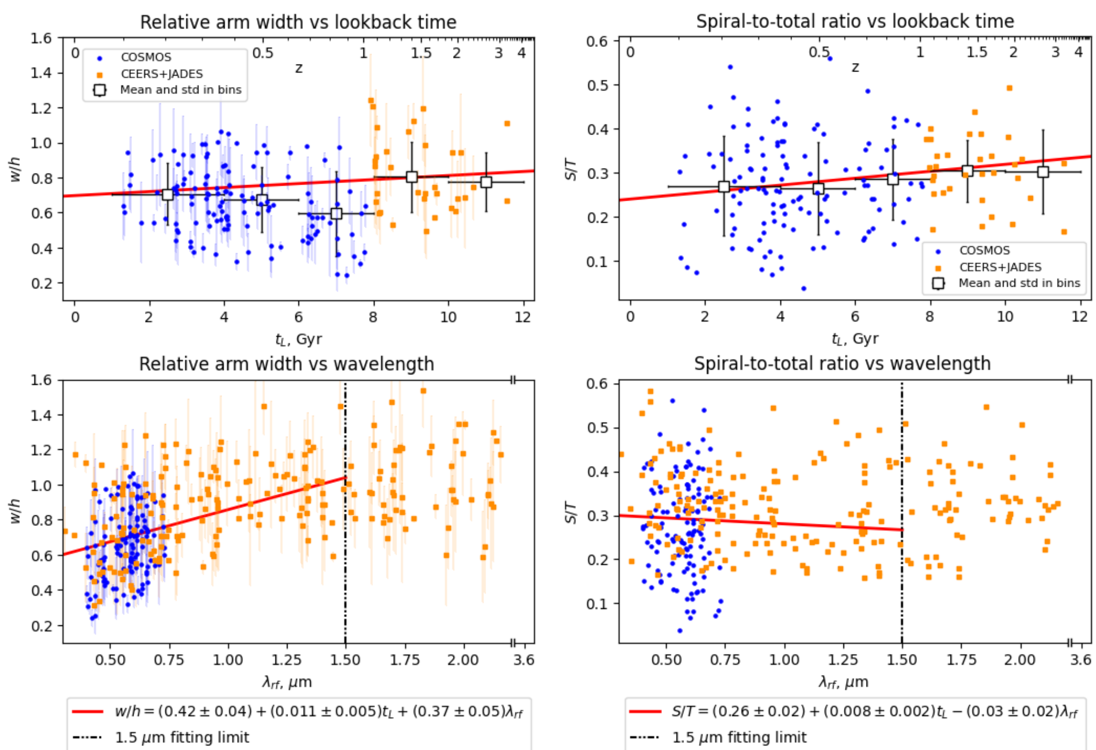

Fig. 3. Dependence of relative width w/h (left) and spiral-to-total ratio S/T (right) on lookback time t_L (top row) and rest-frame wavelength $\lambda_{\rm rf}$ (bottom row). For both parameters a bilinear fit to t_L and $\lambda_{\rm rf}$ was performed. In the bottom row, each point represents a single image, i. e. each galaxy from CEERS and JADES is marked by a few points, corresponding to different wavelengths.

distribution of stellar populations of different ages and colors in a spiral arm. For the spiral-to-total ratio S/T, band-shifting effects also take place, but they are weaker than for w/h, with S/T decreasing by 0.03 per 1 μm.

4 Summary

1. We have performed the spiral arm decomposition for the sample of 159 distant galaxies, up to $z = 3.3$.
2. We have found that the pitch angle has decreased and the azimuthal length has increased since the early times of the Universe, at rates of -0.5 deg/Gyr and 7 deg/Gyr, respectively. In other words, the spiral arms have become more wound over time.
3. We have measured the band-shifting effects for spiral arms. We observe that in some cases, namely for the spiral arm width, these effects are stronger than the evolutionary effects. For the spiral-to-total ratio, they are at least comparable to evolutionary changes.

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