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Study of Galaxy Structure and Morphology at z>2 with JWST

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ABSTRACT

The study of galaxy evolution is a crucial part of understanding the evolution of the universe. Galaxy evolution involves various aspects, including understanding the changes in galaxy size and shape over cosmic time. This research aims to understand how galaxies evolve by analyzing the structure of galaxies from survey data. With a dataset of 8,743 galaxies at z>2 from JWST observations across four survey fields, we statistically analyze the structure and morphology of galaxies at different redshifts. We conduct morphological classifications through visual inspection and model galaxy structures using the GALFITM software. Through this method, we find that irregular-shaped galaxies dominate at high redshifts, with a fraction reaching up to 80%. Meanwhile, the fraction of galaxies with disk and spheroidal features remains around 30%-60% across redshifts. Using single Sérsic profile modeling, we find that the mass-radius relation for quiescent galaxies has a steeper slope compared to the star-forming galaxies. These findings support the bottom-up galaxy formation theory, where smaller galaxies form first and later merge to create larger galaxies. This research also aligns with conditions in the local universe, where the quiescent galaxies tend to be elliptical/spheroidal in shape, while star-forming galaxies have variety of morphologies.

Keywords: Galaxies, Effective Radius, Galaxy Morphology, Galaxy Evolution

1. INTRODUCTION

To understand the process of structure formation and the evolution of the universe, it is essential to understand how galaxies evolve, as they are the building blocks of the universe. One characteristic of galaxies that can be studied is their physical structure. By observing changes in the shapes of galaxies over time, we can infer how they evolve, whether galaxies collapse rapidly into small fragments or smaller galaxies form first and later merge to create larger galaxies. However, galaxy evolution occurs over extremely long-time scales, making direct observation throughout the entire process impractical. Therefore, statistical studies are one of the solutions to understand galaxy evolution without observing it from beginning to end.

Galaxy surveys that capture galaxies from various phases of the universe allow us to investigate their structure at different eras in cosmic history, providing insight into how the galaxies' structure was at those times. Previous research has shown that the mass-radius relation of galaxies at $0.25 < z < 2.75$ has a mathematically significant correlation [1]. Quiescent galaxies have a steeper mass-radius relations compared to star-forming galaxies. This suggests that the mass of quiescent galaxies is distributed throughout the galaxy, so any slight increase in mass results in a larger effective radius. In contrast, for star-forming galaxies, the mass is concentrated at the center, meaning that an increase in mass does not significantly change the size of the galaxy.

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Besides, previous studies have also shown that the fraction of spheroidal and irregular galaxies remains relatively constant within the range $3 < z < 9$, whereas the fraction of galaxies with disk features decreases at higher redshifts [2]. This suggests that disk features were not yet widely formed in the early universe. Utilizing the latest observational data from JWST, we will conduct an analysis of the structure and morphology across a larger sample of galaxies and a broader redshift range compared to previous studies.

2. DATA

We used data from the James Webb Space Telescope (JWST) observation. The data used in this study consists of photometric (imaging) data obtained with the NIRCam instrument, which has been reduced using the Grizli pipeline (Brammer 2023). Additionally, we used catalog data from EAZY, which results from spectral energy distribution (SED) fitting with EAZY software [3] on the NIRCam observational data. Therefore, this study does not use raw JWST data, but rather reduced data that that has been fitted.

We used JWST observational data from four galaxy surveys: CEERS, COSMOS-Web, FRESCO-GOODS-South, and PRIMER. These four surveys were observed with various filters, but one of the filters used in all four fields is the F444W filter. Thus, in this study, most part of the analysis refers to data from this filter. The photometric data in this study have a pixel size of 0.04", except for galaxy data in the F090W, F115W, F150W, F182M, F200W, and F210M filters from the FRESCO field, which have a pixel size of 0.02". The total data set from these four fields is 216,098 galaxies.

2.1 Sample Selection

We selected a galaxy sample that exceeds those used in previous studies. To enable a deeper analysis of galaxy structures, we selected galaxies at $z > 2$. However, since galaxies appear fainter at greater distances, we also limited our sample to galaxies with magnitudes smaller than 25. This selection allows the distinct features of each galaxy to be visually discernible. From this sample selection, a total of 8,743 galaxies were obtained. Table 1 shows the number of galaxies from each survey based on this selection criteria.

Table 1. The number of galaxies after selection based on redshift and magnitude

Fields	Number of Galaxy
CEERS	2663
COSMOS-Web	1299
FRESCO GOODS-South	1498
PRIMER UDS	3283

In addition to these two criteria, we also performed a visual selection to exclude galaxies with truncated images and those contaminated by nearby bright objects. These two steps help to minimize errors in the galaxy morphology fitting process.

In this study, several parameters are derived from the fitting process, while others are obtained directly from the EAZY catalog. The parameters derived include the effective radius of the galaxy and the Sérsic index, while parameters such as redshift and galaxy mass are taken directly from the catalog. We found that a small fraction of galaxies in the EAZY catalog lack mass values. In cases where galaxies lack mass information, photometric images often reveal that these objects are not galaxies (e.g., stars or galaxies contaminated by stellar light).

2.2 Cutout Images

The JWST photometric data we used encompasses the entire field of observation. Therefore, we cropped the images such that each galaxy is contained within a single image. Each image is created with a size of 100×100 pixels for data with a pixel size of 0.04", and a size of 200×200 pixels for data with a pixel size of 0.02". We must ensure that each cutout image contains only one galaxy. The purpose of creating these cutout images is to analyze the structure and morphology of each galaxy.

2.3 Quiescent and Star-Forming Galaxies

In this study, we classify galaxies into two categories based on their star formation activity. Galaxies that have ceased to form stars are categorized as quiescent galaxies, while galaxies that are still actively forming stars are categorized as star-forming galaxies. This classification is performed with the distribution of galaxy in the color diagram as described in [4], and selected from the star formation rate by mass curve as described in [5].

3. METHODOLOGY

We used GALFITM to model the morphology of each galaxy. Subsequently, we selected galaxies that were well-modeled and classified them based on their morphology through visual inspection. Galaxies that were not well-modeled such as those contaminated by nearby galaxies were excluded from the analysis. In this study, we assume the Lambda Cold Dark Matter (ΛCDM) cosmological model with a Hubble constant of $H_0 = 70\ km\ s^{-1} Mpc^{-1}$ and a matter density parameter of $\Omega_{M,0} = 0.3$.

3.1 Parametric Fits

GALFITM [6] is a development of the GALFIT program [7], [8]. GALFIT is a two-dimensional fitting algorithm that uses a nonlinear least-squares approach with the Levenberg-Marquardt technique. GALFIT and GALFITM modeled galaxy shapes based on galaxy intensity distribution. GALFITM can be run in an integrated manner for multiple filters, providing the best-fit parameters from the fitting results along with their uncertainties.

Some of the inputs required to run GALFIT or GALFITM include galaxy photometry data, a sigma image, and a PSF. In this study, we use galaxy photometry data that has been cropped into cutout images, sigma images generated from weight images, and PSF images available from JWST observations.

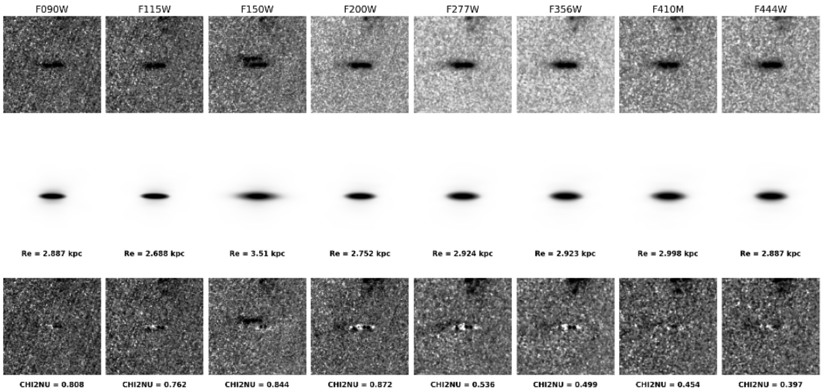

Figure 1. Galaxy with ID PRIMER13392 data from observation (top). Galaxy morphological model from fitting (middle). Residual from galaxy fitting (bottom).

To standardize the fitting process for each galaxy, we set uniform initial parameters for all galaxies, such as initial galaxy position in the cutout images and initial position angle of the galaxy. This approach may not perfectly match the actual shape of each galaxy, but it could be good enough for the initial approach. We use a single Sérsic profile in the GALFITM fitting process as the simplest fitting model for galaxy morphology. Figure 1 shows an example of a galaxy morphological fitting using a single Sérsic profile with GALFITM.

3.2 Visual Inspection

In addition to applying the fitting method to model galaxy morphology, we performed galaxy morphology classification through visual inspection. Referring to the previous study by [2], we classified galaxies into 7 classes: galaxies with disk-like features, galaxies with spheroidal shapes, galaxies with irregular shapes, and combinations of two or three of these categories. Figure 2 shows an example of a galaxy in each category.

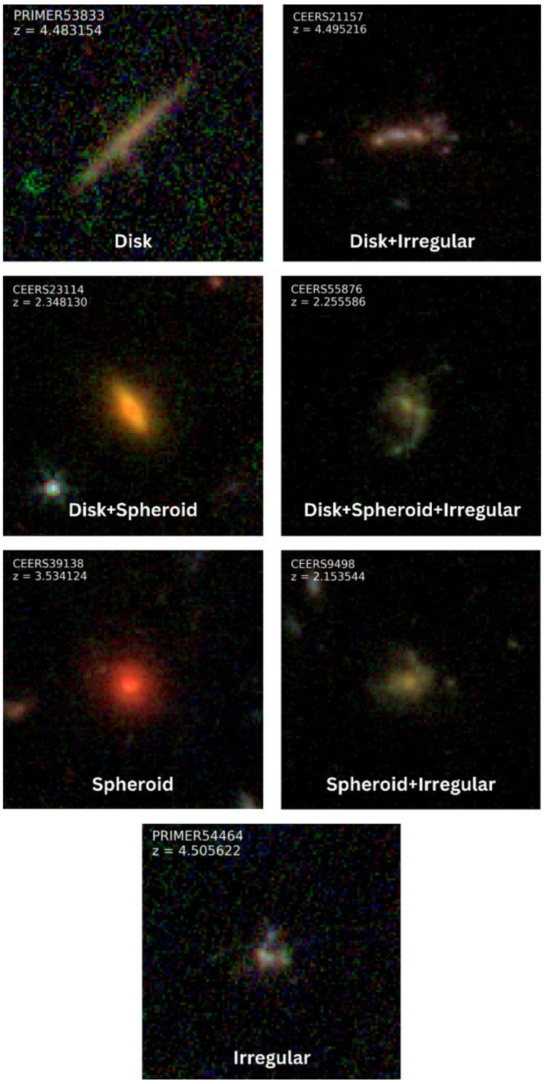

Figure 2. Example of a galaxy in each morphological category based on visual inspection.

4. RESULTS

4.1 Galaxy Morpohology Distribution at High Redshift

This study shows that the number of galaxies with irregular shapes increases with redshift, as shown in Figure 3. Meanwhile, the fraction of galaxies with disc and spheroid features remains around 30%-60%across redshifts, but still shows a decreasing trend. These findings suggest that galaxies had more random, irregular shapes in the early universe. Over time, galaxies evolved into more firm structures, forming discs, bulges, or both as seen in galaxies in the local universe. This supports the theory of bottom-up galaxy formation, where smaller galaxies form first and larger galaxies form from the merger of smaller galaxies.

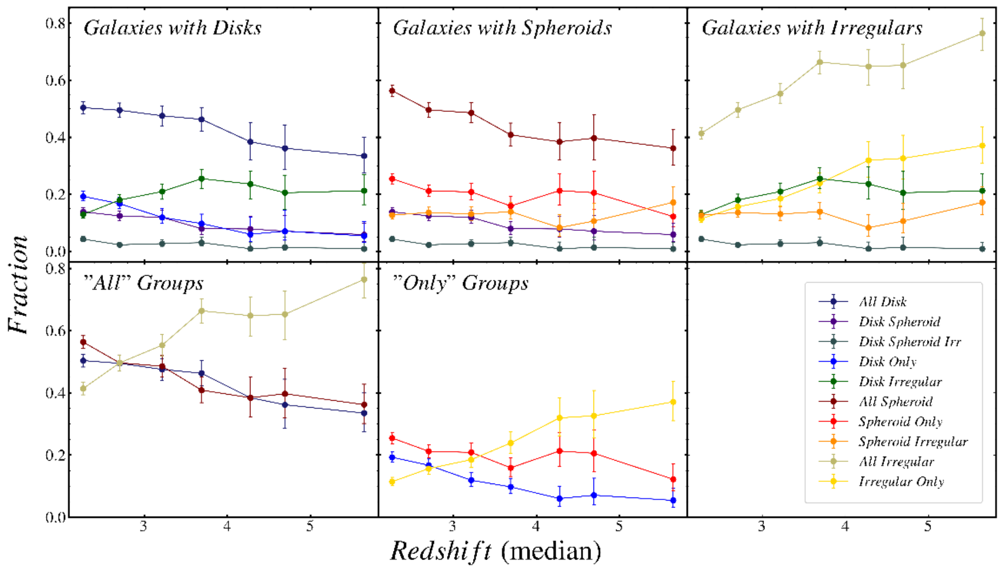

Figure 3. Morphological distribution of galaxies by visual inspection.

Besides, by comparing our morphological classification results with visual inspection, we observe that quiescent galaxies tend to have spheroidal shapes, while star-forming galaxies have a variety of morphological forms. These findings are shown in Figure 4. This supports the assumption that spheroidal galaxies are the progenitors of elliptical galaxies or the bulge components in spiral galaxies, where star formation occurred rapidly.

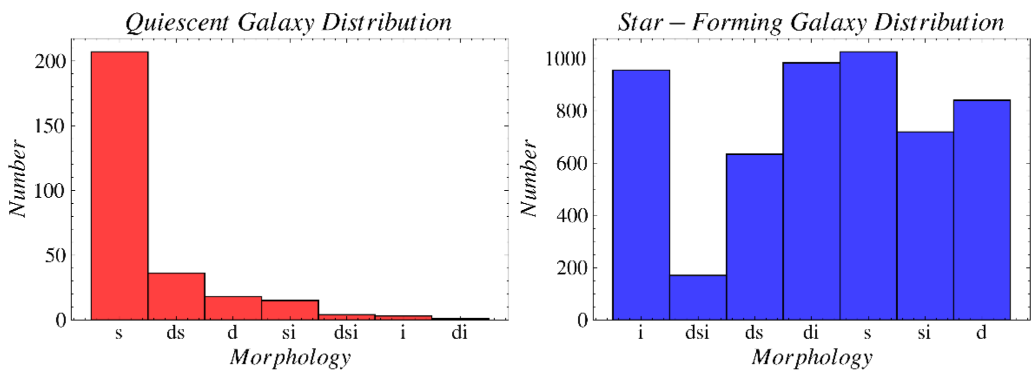

Figure 4. Quiescent and star-forming galaxy distribution based on morphology (s:spheroid, d:disk, i:irregular, ds:disk+spheroid, di:disk+irregular, si:spheroid+irregular, dsi:disk+spheroid+irregular).

4.2 Mass-Radius Relation

This study is also concerned with the mass-radius relation. Figure 5 shows the effective radius data from the fitting results in F444W filter, compared with the mass-radius relation obtained from van der Wel et al. 2014. The mass values in Figure 5 are obtained from EAZY catalog, while effective radius values are derived from the fitting results. We find that star-forming galaxies have a steeper mass-radius relation compared to the quiescent galaxies. These findings agree with the suggestions that the mass of quiescent galaxies is distributed throughout the galaxy, while in star-forming galaxies, the mass is concentrated at the center. Additionally, our findings in this study align well with those reported in previous studies. At higher redshifts, galaxy sizes tend to be smaller, but the mass-radius relation does not change significantly.

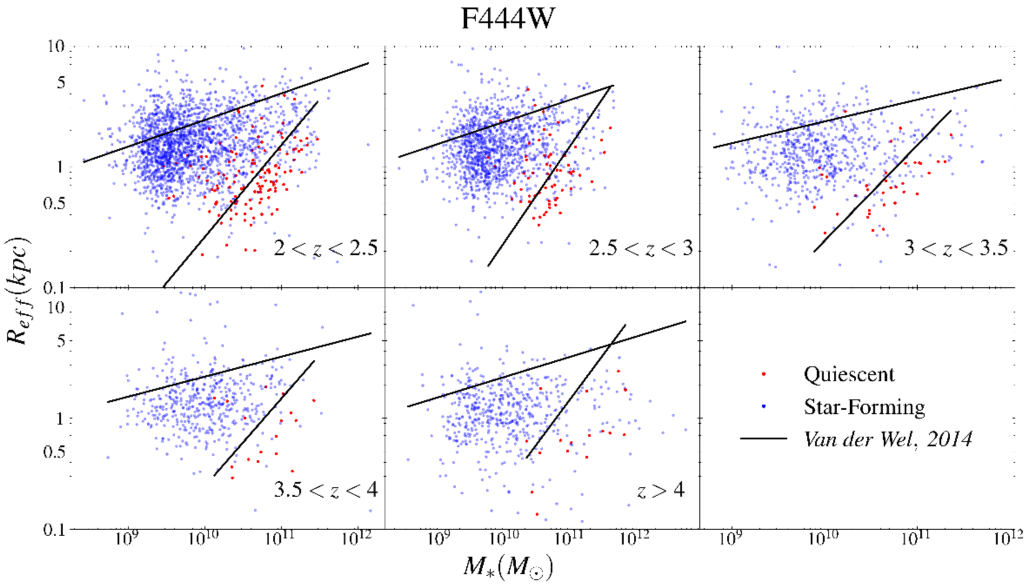

Figure 5. Mass-radius relations from morphological fitting in F444W, shown with mass-radius relation from previous study.

4.3 Radius-Wavelength Relation

We also found that for high-mass star-forming galaxies, the radius-wavelength relation shows a significant decreasing trend. Figure 6 shows the relationship between the effective radius of galaxies and wavelength from each filter. We observe that as the wavelength increases, the effective radius of galaxies becomes smaller. This may point to the chemical composition within galaxies because shorter wavelengths correlate with the observations of gas and dust content in galaxies. This means that the gas and dust components are more widely distributed than the stellar components within the galaxy. In Figure 6, the error bar shows the median from the uncertainty distribution in each bin.

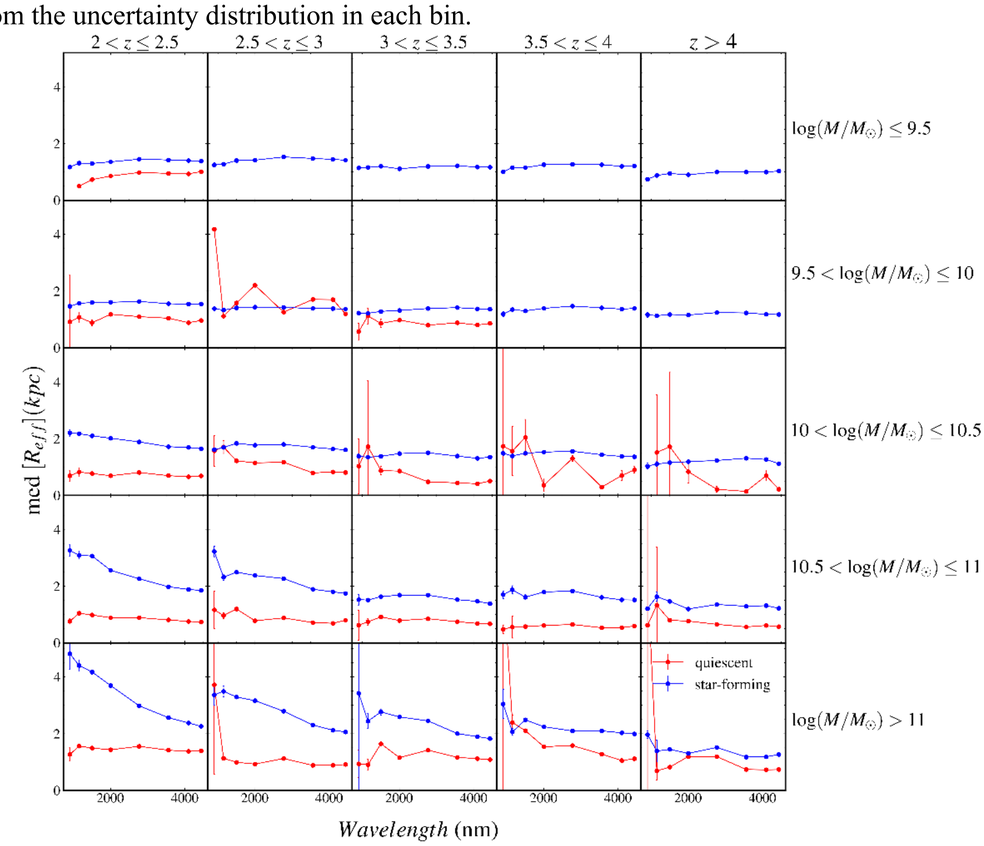

Figure 6. Radius-wavelength relations from morphological fitting in F444W, shown by the median from the distribution in each bin.

5. DISCUSSION

This study shows that the number of galaxies with irregular shapes increases with redshift. Meanwhile, the fraction of galaxies with disc and spheroid features remains around 30%-60% across redshifts and shows a decreasing trend. These findings suggest that galaxies had more random, irregular shapes in the early universe. Over time, galaxies evolved into more firm structures, forming discs, bulges, or both as seen in galaxies in the local universe. This supports the theory of bottom-up galaxy formation, where smaller galaxies form first and larger galaxies form from the merger of smaller galaxies.

The mass-radius distribution pattern of galaxies in this study aligns well with the mass-radius distribution pattern in van der Wel et al. 2014. This distribution pattern indicates that quiescent galaxies have smaller radius compared to star-forming galaxies. The mass of quiescent galaxies is distributed throughout the galaxy, so any slight increase in mass results in a larger effective radius. Meanwhile, for star-forming galaxies the mass is concentrated at the center, meaning that an increase in mass does not significantly change the size of the galaxy.

Our findings indicate that JWST results are in agreement with the bottom-up theory of galaxy formation. We observe that quiescent galaxies typically had spheroid shapes, while star-forming galaxies show a greater variety of shapes. This aligns with observations of galaxies in the local universe, where elliptical galaxies, which contain mostly old stars, have passive star-forming activity. This study also supports previous research regarding the relationship between mass and the effective radius of galaxies, also the radius-redshift trend. In addition to the findings of this study, we could potentially enhance this research in the future by performing a more accurate galaxy fitting for each galaxy, thereby improving the analysis's accuracy.

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