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EPOCHS VI: The Size and Shape Evolution of Galaxies since $z \sim 8$ with JWST Observations

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ABSTRACT

We present the results of a size and structural analysis of 1395 galaxies at $0.5 \le z \lesssim 8$ with stellar masses $\log(M_*/M_\odot) > 9.5$ within the *JWST* Public CEERS field that overlaps with the HST CANDELS EGS observations. We use GALFIT to fit single Sérsic models to the rest-frame optical profile of our galaxies, which is a mass-selected sample complete to our redshift and mass limit. Our primary result is that at fixed rest-frame wavelength and stellar mass, galaxies get progressively smaller, evolving as $\sim (1+z)^{-0.71\pm0.19}$ up to $z \sim 8$. We discover that the vast majority of massive galaxies at high redshifts have low Sérsic indices, thus do not contain steep, concentrated light profiles. Additionally, we explore the evolution of the size-stellar mass relationship, finding a correlation such that more massive systems are larger up to $z \sim 3$. This relationship breaks down at $z > 3$, where we find that galaxies are of similar sizes, regardless of their star formation rates and Sérsic index, varying little with mass. We show that galaxies are more compact at redder wavelengths, independent of sSFR or stellar mass up to $z \sim 3$. We demonstrate the size evolution of galaxies continues up to $z \sim 8$, showing that the process or causes for this evolution is active at early times. We discuss these results in terms of ideas behind galaxy formation and evolution at early epochs, such as their importance in tracing processes driving size evolution, including minor mergers and AGN activity.

1. Introduction:

Before JWST: know little about galaxy structure and morphology at z > 3

HST observation: galaxies are more irregular and peculiar at higher z

Theoretical studies: a. At higher redshift, galaxies become more compact; **b.** Galaxy sizes increase with stellar mass; **c.** Compact galaxies may grow in size due to mergers or renewed star formation.

Early JWST results (Ferrira+22): **a.** HST did not fully reveal structural features of galaxies at z > 1.5, fewer peculiar morphologies; **b.** galaxies appear morphologically much more disc-like than previously thought

A significant amount of quantitative analysis is still needed.

2,3. Data & Galaxies properties:

JWST CEERS + HST CANDELS data

(5σ depth in the table)

Filter Name	Depth
HST/ACS F606W	28.8
HST/ACS F814W	28.2
HST/WFC3 F125W	27.6
HST/WFC3 F140W	26.8
HST/WFC3 F160W	27.6

Filter	Depth
F115W	28.75
F150W	28.60
F200W	28.80
F277W	28.95
F356W	29.05
F410M	28.35
F444W	28.60

Parent sample:

A catalogue of 1649 massive objects with $\log(M_*/M_\odot) > 9.5$.

z_{phot} from EAzY

SED fitting using a custom template fitting code: BC03, Chabrier03 IMF, constant burst + exponentially decreasing SFH

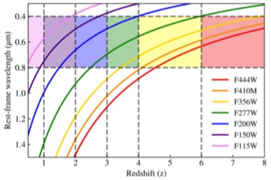
→ The stellar mass do not have systematic biases compare with CANDELS

4. Morpholoical fitting

GALFIT v3.0.5

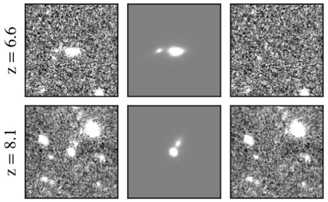
$$\chi_\nu^2 = \frac{1}{N_{\rm DOF}} \sum_{x=1}^{nx} \sum_{y=1}^{ny} \frac{(f_{\rm data}(x,y) - f_{\rm model}(x,y))^2}{\sigma(x,y)^2}$$

$$I(R) = I_e \exp\left\{-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}$$



Results here are based on the filters that best match the rest-frame optical wavelength of the source

5. Sample Selection



→ 1395 robust galaxy fits.

a. Exclude bad fits from GALFIT:

$0.05 < n < 10$, b/a > 0.01

b. Residual Flux Fraction (Hoyos+11) **< 0.5**:

$$\mathrm{RFF} = \frac{\sum_{(\mathrm{j,k}) \in \mathrm{A}} \left| \mathrm{I_{j,k}} - \mathrm{I_{j,k}^{GALFIT}} \right| - 0.8 \sum_{(j,k) \in A} \sigma_{\mathrm{B}}\mathrm{j,k}}{\mathrm{FLUX\_AUTO}}$$

$$0.8 = \sqrt{\frac{1}{2\pi}} \int_{-\infty}^{\infty} |x| \times \mathrm{e}^{-x^2/2}\, \mathrm{d}x,$$

$I_{j,k}$ the data image,

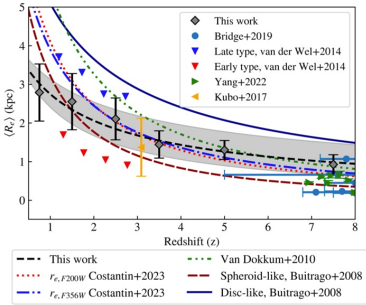
$\sigma_B j,k$ the sigma image.

If the real galaxy had a pure Sersic profile, the residual image would be very similar to Gaussian white noise

6. Results

6.1 Half-light radii and Sérsic indices

$$\langle \mathrm{R_e} \rangle = 4.50 \pm 1.32(1+z)^{-0.71\pm0.19}$$



The first time measurements of the power-law curves at z > 3

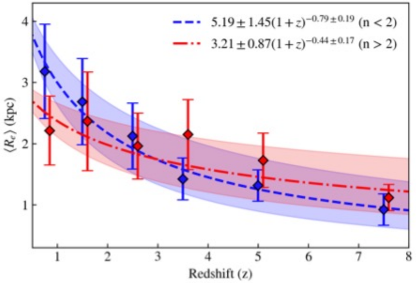
Difference between other studies:

a. Highly dependent on the redshift ranges studied and the stellar mass. e.g., van der Wel+14 are for galaxies with $\log(M_*/M_\odot) \sim 10.75$.

Thus, galaxies in this work are on average smaller than the previous.

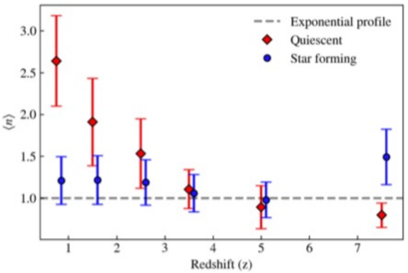
b. The power-law in this study is less steep than previous studies because the size evolution is weaker at higher redshifts. (High-z has shorter time scale.)

Still, the galaxy size evolving at the highest redshifts, confirming that galaxy evolution in structure were already taking place in the first Gyr since the Big Bang.



Effective radius is less dependent upon the Sersic index at high redshift

Galaxies at higher redshift are almost all compact objects, which do not show morphology difference until around $z \sim 3$. (consistent with the inside out growth scenario of star-forming galaxies at z < 5.)



Sersic index - redshift distribution for passive and star forming galaxies

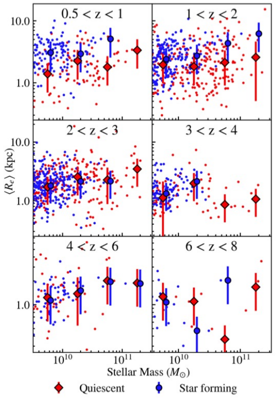
A galaxy with a sSFR greater (lower) than the median sSFR within the redshift bin, to be a star-forming (quiescent) galaxy.

a. A higher proportion of disc-type galaxies in the early universe (X to HST).

b. The star forming galaxies have Sersic indices around $n \sim 1$. At highest redshift, a slight increase on Sersic index. ← Stars forming in young, compact sources, before evolving into disc-like galaxies.

c. Still, at z ~ 3, the galaxy population in structure show different trends. Inside out star formation in SF galaxies. Stellar migration in passive systems.

6.2. Galaxy Size-Mass Distribution



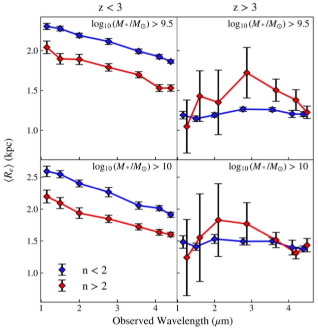
a. Galaxy size increases with stellar mass, in both populations up to $z \sim 6$. (3 < z < 4?)

b. SF galaxies at the lower redshifts are larger at a given mass (break down at the lower masses).

c. At $z > 3$, the sizes of the quiescent and SF populations are statistically the same (transient quiescence driven by AGN).

6.3. Changes in Effective Radii as a Function of Wavelength

The inside out growth scenario: shorter wavelength would appear larger.



Note: dust attenuation can increase the observed half-light radius

Galaxies with higher Sersic indices have smaller radii at z < 3, but not at z > 3.

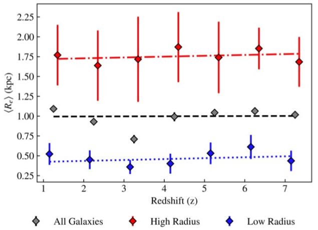
→ Galaxies at high redshift are forming stars through the entire galaxy.

6.4. Correlation with Visual Morphology (as expected)

6.5. Comparison with Image Simulations

If the trend in this paper, i.e., galaxies get progressively smaller up to $z \sim 8$, is due to a real evolution or due to the fact that the surface brightness of the galaxies makes the galaxies appear smaller.

Take a sample of 186 low-redshift galaxies at redshifts 0.5 < z < 1, and create simulated images of these galaxies at higher redshifts up to z = 7.5



The trends above are due to a change in galaxy properties with redshift, not because the galaxies appear smaller at higher redshifts due to redshift effects.

7. Discussion

a. From $z \sim 7$ to $z \sim 3$, galaxies sample is not large enough.

b. Hubble sequence begins at $z \sim 3$. Different formation mechanisms coming into play at $z < 3$.