Lessons in Galaxy Evolution from the First Year of JWST Observations

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ELT Science in Light of JWST: UCLA
Evolution of Galaxy Structure

Time

$z \sim 0$

$z = 0.3 - 0.7$

$z = 2.0 - 2.7$

Image Credit: ESA Press Release on Lee et al. (incl. Kartaltepe) 2013
What can we Learn about/from Galaxy Structure?

• When was the Hubble Sequence put into place?
  • When did the first disks and bulges form?
  • What was the role of mergers in the very early universe?

• What can the relationship between galaxy structure and other properties tell us about...
  • Mass assembly?
  • Supermassive black hole growth?
  • Star formation in galaxies?
  • Accretion of gas from the IGM?
Surprises/Discoveries from JWST

- High Redshift Galaxies are *compact*
Surprises/Discoveries from JWST

- High Redshift Galaxies are *compact*
- High Redshift Galaxies are *extended*
**Surprises/Discoveries from JWST**

- High Redshift Galaxies are *compact*
- High Redshift Galaxies are *extended*
- High Redshift Galaxies are *diverse*

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Kartaltepe et al. 2023

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Tohill et al. 2023

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Larson et al. 2023
Surprises/Discoveries from JWST

- High Redshift Galaxies are compact
- High Redshift Galaxies are extended
- High Redshift Galaxies are diverse
- High Redshift Galaxies are resolved
**Surprises/Discoveries from JWST**

- High Redshift Galaxies are *compact*
- High Redshift Galaxies are *extended*
- High Redshift Galaxies are *diverse*
- High Redshift Galaxies are *resolved*
- Finding example galaxy mergers

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Kartaltepe et al. 2023

Boyett et al. 2023, $z=9.3$

Fujimoto et al. 2023, $z=8.0$

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*Figure 2.* The Astrophysical Journal Letters, irregular component of galaxies with irregular features. When we refer to galaxies as irregular such as asymmetries or surrounding systems, as well as galaxies that are irregular for other reasons, the same as disk ancestor galaxy of the Milky Way. A massive interacting galaxy 510 million years after the Big Bang. Comparison HST vs. JWST images for nine objects in each class within our sample. Left columns shows the HST F160W image, while the middle panel uses F277W/F225W/F356W postage stamp cutouts of a galaxy. Right: Morpology of Gz9p3, shown in the combined F150W+F200W direct image at a distance of 10.5 Mpc. All wavelengths for emission lines are determined from HST imaging. The magnification correction has been applied depending on whether the best available estimate of any gravitational lensing. All magnitudes are in the AB system.

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2.1 Cosmology and conventions

[Make reference to Haslbauer22]

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2.11 Wavebands

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2.12 Comparison with Surface Brightness Priors

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4.1 The morphologies of galaxies across a wide redshift range. As wavelength coverage enables us to probe the rest-frame optical wavelengths for emission lines of the major stellar populations, the relative contribution of each component must be determined from HST imaging. The broad recipes for star formation are missing some key ingredients at early times. The latter interpretation would be consistent with the high numbers of massive red galaxy candidates that were bright enough to be detectable with HST. Finally, we note that the fraction of point sources and extended features in some of these systems at high redshift. It is likely that this apparent trend at higher redshifts may be due to small interactions themselves will be discussed in a future paper. Ceccarelli et al. 2022, in preparation.

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4.2 Irregulars

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4.3 Spheroids

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4.4 Distant Disk Galaxies

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4.5. Note that the total fractions of objects that are all disks, all spheroids, or all irregulars do not vary much over the redshift range. At $z=2.1$ roughly constant at 20% and then decreasing, while the fraction of disk irregulars shows that galaxies such as the Milky Way could potentially have retained the same overall morphological state for over 12 billion years if these distant disk galaxies are similar to the Milky Way.

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4.6 Galaxy Groups

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4.7 Galaxy Clusters

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4.8 Cosmic Evolution

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5.0 Summary

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6.0 Acknowledgments

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9.0 References
Surprises/Discoveries from JWST

- High Redshift Galaxies are *compact*
- High Redshift Galaxies are *extended*
- High Redshift Galaxies are *diverse*
- High Redshift Galaxies are *resolved*
- Finding example galaxy mergers
- Finding example *minor* mergers

Suess et al. 2023
Surprises/Discoveries from JWST

- High Redshift Galaxies are *compact*
- High Redshift Galaxies are *extended*
- High Redshift Galaxies are *diverse*
- High Redshift Galaxies are *resolved*
- Finding example galaxy mergers
- Finding example *minor* mergers
- Finding exquisite gravitational lenses
Morphological Evolution

**HST CANDELS**

**JWST CEERS**

See also: Ferreira et al. 2023, Robertson et al. 2023

Kartaltepe et al. 2023
Morphological fractions as a function of stellar mass at cosmic afternoon \((z < 1.5; \text{left panel})\), cosmic noon \((z = 1.5 - 4.0; \text{middle panel})\), and cosmic morning \((z > 4; \text{right panel})\). Symbols are the same as Figure 12. As in Figure 12, we do not plot the fractions for stellar mass bins with fewer than five objects.

From disks to spheroids or irregulars occur across all the cosmic epochs, particularly in the mass range of \(\log M^*/M^\odot \approx 10.5\). Third, spheroid galaxies exist in the cosmic morning at relatively low masses, but dominates the galaxy population in the cosmic noon and afternoon in the high-mass regime of \(\log M^*/M^\odot \approx 10\). Fourth, the irregular fraction increases from the cosmic morning to the cosmic noon but decreases again in the cosmic afternoon due to the reduced number of massive irregular galaxies. Lastly, these trends of morphological fractions can imply an evolutionary sequence from disks to spheroids or irregulars, with massive irregular galaxies eventually transforming into spheroids in the cosmic afternoon. Overall, these findings align very well with the morphological evolution of galaxies suggested in the HR5 simulation.

5.2. Formation and Evolution of Disks from the Early Universe

In this study, we observed a prevalence of disk-type morphology for the galaxies with stellar masses \(\log M^*/M^\odot \approx 10\) at \(z > 4\), which aligns with the HR5 results. Interestingly, our findings from JWST images, capturing the distribution of stellar light, exhibit a good agreement with the HR5 simulation based on stellar mass distribution. Park et al. (2022) explained that the emergence of disk-type morphologies in the early universe can be attributed to the initial angular momentum in protogalactic clouds. The initial angular momentum is gained from the inflow of cold gas into protogalaxies along primordial large-scale structures, which is consistent with the basis of the tidal torque theory (Peebles 1969; White 1984). According to this theory, the tidal field on protogalactic regions and corresponding velocity field are governed by the large-scale dark matter distribution, which keep galaxies to acquire angular momentum set up by the initial conditions. The competition between the tidal torque driving galaxies into disk type and mergers driving galaxies into irregulars and spheroids determines the morphology distribution. The dominance of disks in the cosmic morning can be elucidated with these underlying physical processes.

In Figure 14, our analysis reveals a \(\sim 20\%\) decrease in disk fraction at small masses during the cosmic noon and afternoon compared to the cosmic morning, in contrast to a notable increase in the spheroid fraction in the high-mass regime. In the low-mass regime \((\log M^*/M^\odot < 10)\), there is a slight increase of \(5\%\) in the irregular fraction from the cosmic morning to the cosmic noon, indicating a tendency for disk galaxies in this mass range to transform into irregular galaxies. However, it is important to note that mergers do not inevitably lead to irreversible morphological changes from disks to other types. Despite undergoing morphological transformations due to mergers or destructive interactions, the initial disk structures can be restored through the acquisition of angular momentum via gas accretion from the vorticity-rich surrounding matter (Welker et al. 2014; Park et al. 2022). Indeed, the HR5 simulation supported this recovery process, demonstrating morphological fluctuations in initial disk galaxies with changing S´ersic indices (refer to Figure 12 in Park et al. 2022). Consequently, this disk recovery mechanism can effectively explain why the disk fraction remains high in the cosmic morning in spite of high merger rate at corresponding redshifts (Duncan et al. 2019).
Kartaltepe et al. 2023

Normalized Number

Sersic Index (n)  Effective Radius, Re [kpc]  Axis Ratio (b/a)  Asymmetry

3.0 < z < 4.0

4.0 < z < 5.0

5.0 < z < 6.0
Preliminary measurements for 355,000 galaxies in COSMOS-Web
Yang et al. (incl. Kartaltepe), in prep
Morphologies with Contrastive Learning

• Trained on IllustrisTNG mock images
• Observed galaxies tend to be more compact and more elongated than IllustrisTNG
• Some visual disks may be prolate/elongated ellipsoids
Inferring the 3D Shapes of Distant Galaxies

• Are galaxies that look like disks at high-z truly disks?

Are most high-z galaxies

\textbf{oblate (disky)} \quad \textbf{or} \quad \textbf{prolate (elongated)}

Pandya et al. (incl. Kartaltepe) 2023
Inferring the 3D Shapes of Distant Galaxies

• Are galaxies that look like disks at high-z truly disks?

~50-80% of log (M* / M☉) = 9.0 – 9.5 galaxies at z=2-8 are intrinsically prolate

Oblate (disky) spheroidal ellipsoids are sub-dominant

significantly lower triaxialities for higher masses and lower redshifts indicating the emergence of disks
Visual Mergers

Merger

Interaction Class 1
(interaction within segmentation map)

Interaction Class 2
(interaction beyond segmentation map)

Non-interacting Companion

Rose et al. (incl. Kartaltepe), in prep
Identifying Mergers Using Machine Learning

• Using IllustrisTNG images with ‘CEERS-like’ noise as a training set (Rose et al. 2023)

• ‘Merger’ typically defined as +/- 250 Myr (with some experimentation), major and/or minor

• Testing Random Forests + Neural Network ‘DeepMerge’ (Ćiprijanović et al. 2020)

Rose et al. (incl. Kartaltepe), in prep
Preliminary Results

• Both Random Forests and DeepMerge can accurately classify up to ~60-70% of mergers

• Seems to be a ceiling: can increase, but at the expense of incorrectly classifying non-mergers

Rose et al. (incl. Kartaltepe), in prep
Galaxy Kinematics

• Deep NIR spectroscopy with JWST will enable kinematic measurements of galaxies out to high-z

• Possible with high resolution mode on NIRSpec as well as NIRCam WFSS (for relatively bright sources)

• Kinematics will be essential for identifying true rotating disks and quantifying mergers
Role of the ELTs

- Multiplexed moderate resolution spectroscopy (slit + IFU) will enable kinematic measurements (gas and stellar!) for large samples of galaxies, look for rotation/dispersion, mergers, rotation curves
  - TMT First light: IRIS, WFOS
  - TMT Second generation: IRMS, IRMOS
  - GMT: GMACS, GMTIFS

- High resolution imaging with AO will enable deep morphology studies for larger samples
  - Studies of low surface brightness features such as tidal tails, globular clusters, extended disks, etc.
  - Identification of minor companions

- Ability to follow-up sources identified with Euclid+Roman all over the sky
Summary

• Wide diversity of visual morphologies seen at z=3-9!
  • Large fraction of galaxies with disks (~60% → ~30%)
  • Large fraction of galaxies with irregular features (~40-50%)

• Some evidence that the large numbers of high-z disks might not be true disks
  • Prolate/elongated systems (See Pandya et al. 2023, Vega-Ferrero et al. 2023)

• Identifying galaxy mergers, visually and through machine learning techniques
  • Testing on simulations, these techniques hit an upper limit of correctly identifying ~60-70% of mergers

• The ELTs will enable kinematic and deep imaging studies of large samples of galaxies