Morphological Evolution of Galaxies to $z \sim 4$

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Abstract. Galaxies have clearly evolved since the universe was 1 Gyr old, but methods to trace and quantify this evolution are still in their infancy. In this paper I demonstrate that with the careful use of a 'physical morphology' it is possible to determine quantitatively how the process of galaxy evolution is occurring out to $z \sim 4$. Using a system of parameters that traces star formation and galaxy interactions, I show how distinct galaxy populations at high-z can be identified in deep high-resolution optical and NIR images. These tools are also used to measure a potential merger fraction of galaxies from $0 < z < 4$. If these methods are reliable, as is suggested by a local galaxy calibration, the merger fraction of galaxies scales α $(1+z)^{2.1\pm0.5}$, peaks near $z \sim 2$, and declines thereafter. I also discuss how this system is likely part of the ultimate physical classification of galaxies.

1 Introduction

Although it is largely misunderstood and often misused, galaxy morphology is becoming a powerful tool for learning how galaxies form and evolve. The *Hubble Space Telescope* now allows us to study high-resolution 'deep fields' of distant galaxies, yet finding a way to utilize this information is not obvious or simple.

The dominate paradigm for understanding galaxies is still largely based on the Hubble Sequence [14] and its various revised forms. Hubble classifications are useful for describing the gross properties of nearby galaxies that are for the most part in quiescent star formation and dynamical states. Even in this situation, Hubble types correlate with physical properties, such as color and star formation rates, only in the *mean* [21]. This is due to the fact that Hubble types *do not* consider recent star formation in its classification, nor do interacting or merging properties factor into a Hubble type. Because the merger rate of galaxies in the local universe is $< 3\%$ [20] and since recent star formation for nearby galaxies is also low [18], the Hubble sequence is effective in the mean for identifying nearby galaxy populations.

The subjective Hubble morphological system is frankly inadequate at high redshift [e.g., 1,6]. Too many galaxies at high-z fall in the catch-all "irregular" or "peculiar" class. It is not yet understood if these unusual looking galaxies are true irregulars forming stars stochastically, or if they are starbursts triggered by some process, perhaps galaxy mergers. In this paper, I will present preliminary work showing how high-z galaxies seen in deep optical and NIR images can be classified by understanding and quantifying star formation and merging properties based on their structures. I also demonstrate how these tools can be used to perhaps trace the merger fraction of galaxies out to $z \sim 4$.

2 Fundamental Parameters and Nearby Galaxy Calibration

A truly physical morphology must correlate the way a galaxy 'looks', either through its structure or spectrum, with internal physical properties. The physical morphological system being developed by Conselice et al. [5,6,7,8] and Bershady et al. [2] thus far can distinguish the fundamental properties of star formation and galaxy interactions/mergers. Figure 1a shows the color-asymmetry diagram (CAD), a diagnostic tool used to calibrate these properties using nearby galaxies including the Frei sample [12] supplemented by WIYN 3.5m images of starburst galaxies. The galaxies at $A > 0.35$ are all consistent with merging systems based on their broad HI line profiles [8]. The starbursts with $A < 0.35$, NGC 3310 and NGC 7678, have well defined spiral patterns and whose starburst trigger was likely a bar instability, or in the case of NGC 3310 a minor merger in the distant past [8]. The CAD is therefore useful to quantify and trace the presence of not only interacting galaxies, but ones undergoing mergers.

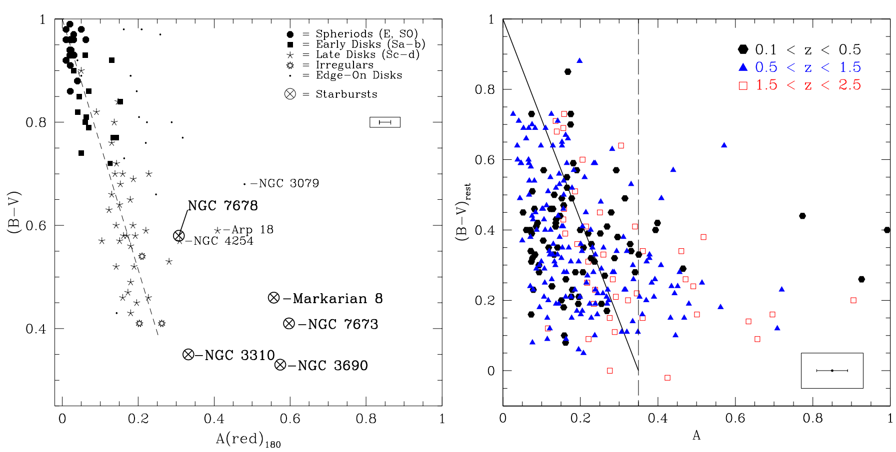

Fig. 1. a. Nearby galaxy color-asymmetry diagram from Conselice et al. [7,8]. Labeled galaxies are those consistent with an interaction or merger, with all galaxies with A> 0.35 having dynamical evidence for mergers [8]. b. Color-asymmetry diagram for galaxies in the HDF with A computed in the rest-frame B band.

The CAD is also useful for tracing star formation in galaxies, although high-frequency structure filtering techniques will likely turn out to be more useful. The CAD 'fiducial' sequence, the dotted line in Figure 1a is likely a star formation sequence. As the star formation rate in a galaxy increases, it becomes bluer and more asymmetric due to the increase of localized star-forming regions. It is important to note that even galaxies whose morphologies are dominated by star formation, such as the irregular NGC 4449, do not have asymmetries that mimic the very high asymmetry produced by merging [7,8]. Although this calibration is limited by the small samples used, the fact remains that the only galaxies with $A > 0.35$ are mergers. This is consistent with other studies that demonstrate galaxies with the highest asymmetries are merging systems [23].

3 The Evolution of Galaxy Populations to $z \sim 4$

Do galaxies form by the merging of other galaxies? How important is rapid collapse in the galaxy formation process [19]? The consensus is that merging is the dominate process, as shown in both semi-analytic and N-body modeling within Cold Dark Matter dominated cosmologies [15,22,4]. Finding a direct method of proving this beyond circumstantial evidence, such as evolving luminosity functions at high-z [16], remains a key observational challenge.

We can investigate this by the use of CADs measured at high-z. Several caveats must be stated before explaining the results of using quantitative features such as asymmetry at high-z. An advantage for astronomers studying galaxy evolution is the ability to study distant, and hence young galaxies. Thus we can directly compare properties of young and old galaxies to determine evolution. This is easier said then done however, due to cosmological effects and biases. When measuring the same parameters at high and low-z, zeroth-order features such as magnitudes and colors can be measured with some certainly by correcting for cosmological k-corrections and dimming. Higher order features, even simple measurements such as radii, are much harder to measure reliably. To robustly determine these features at high-z *requires* simulating low-z galaxies at high-z to determine how parameters change when images are degraded in resolution, and have higher noise levels. This is especially important for measuring morphological or structural features. Conselice et al. [7] show that within certain limits, achievable with deep HST images, the asymmetry parameter measured on HDF galaxies with $m(B) < 25$ should reproduce the same values measured if the galaxies were nearby.

For the low-z HDF range $0.1 < z < 0.5$ (Figure 1b), there are some galaxies with asymmetries consistent with mergers. There is also evidence for a possible correlation between asymmetry and color as seen in the nearby galaxy sample. There are no symmetric red galaxies in this redshift range. This is largely the result of a bias introduced by the small HDF field of view and the fact that the HDF was chosen to avoid any bright galaxies, that in the nearby universe are typically red. At the moderate redshift range

$0.5 < z < 1.5$, there are some red and symmetric galaxies (Figure 1b), and there is an increase in the presence of systems consistent with merging. At the highest redshift range ($1.5 < z < 2.5$), we see an even higher fraction of interactions, and no galaxies consistent with red ellipticals.

4 Merger Fractions

A fundamental aspect for understanding galaxy evolution is to constrain the history of galaxy merging in the universe. Galaxy pair studies indicate that a high fraction of distant galaxies are likely interacting [e.g., 20,17]. Dynamical pair fractions also reveal that the merger fraction of galaxies increases to at least $z = 1$ with a rate $\sim (1{+}z)^{3.2}$ [17]. Dynamical pair studies are limited by several factors, the least of which is the inability to acquire spectroscopy for large numbers of faint galaxies. Perhaps a more important problem is the fact that these galaxies are not necessarily merging systems, but might be grazing interactions or even galaxies in orbits with several Gyr merger time scales. Despite this, dynamical pairs likely do measure some aspect of galaxy merging.

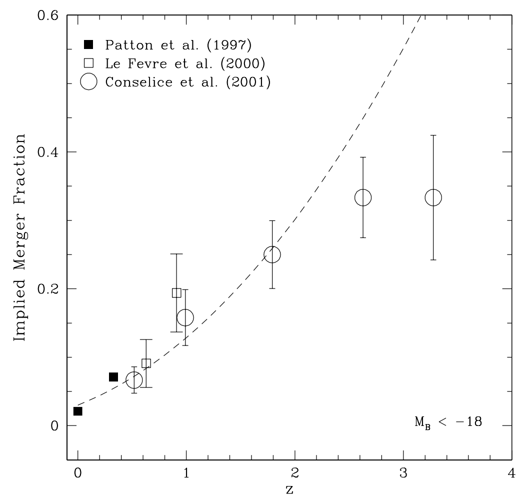

Fig. 2. Observed merger fraction evolution with redshift. The dashed line shows the relationship f = 0.03 $(1{+}z)^{2.1}$, fitted out to z $\sim$ 2.

Using the asymmetry parameters on high-z galaxies, it is possible to demonstrate how *morphologically* the merger fraction at each redshift evolves by directly measuring the fraction of galaxies with structures consistent with merging, as a function of redshift. Doing this for galaxies in the HDF-N, we obtain Figure 2 which shows the fraction of galaxies with rest-frame B-band asymmetries consistent with mergers as a function of z, using the criteria: $A > 0.35$, $M_B < -18$. Also plotted on this figure is the merger fractions found from dynamical pair studies by Patton et al. [20] and Le Févre et al. [17]. If we assume galaxies at these redshifts with $A > 0.35$ are mergers, then the merger fraction increases as f = $0.03(1+z)^{2.1\pm0.5}$ [10]. The merger fraction also potentially begins to decline at redshifts higher than $z \sim 2$ [10].

If the asymmetry parameter can indeed trace mergers out to these redshifts, this preliminary observation is scientifically exciting, and suggests that galaxy mergers are dominating the evolution of galaxies. As is well known, the star formation rate of galaxies peaks at about this redshift [18,11], as does the presence of active galaxies [3]. Are these effects and the mass assembly of galaxies driven by mergers? This morphological system suggests they are, demonstrating the power of galaxy classification when used and calibrated properly.

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