Morphologies of Simulated Galaxy Merger Remnants

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ABSTRACT

We present a parametric morphological analysis of several GADGET N-body/hydrodynamical galaxy mergers, focusing in particular on an equal-mass prograde-prograde disk galaxy merger. These merger simulations have been processed by the Monte-Carlo radiative-transfer code \textit{sunrise} to determine the observable projected light. Over several time steps the main equal-mass disk merger presented in this paper was investigated, and the effects that instrumental properties and observed signal-to-noise ratio have on recovering the intrinsic morphological properties was examined. \textit{galfit} was used to fit a single Sérsic component to the merger remnant’s light profile and the results from simulated observations were compared to the un-degraded images, and to the other merger simulations presented in this paper. For the equal-mass prograde-prograde disk galaxy merger, it was found that while the mass profile of the remnant is roughly deVaucouleurs ($n \approx 4$), the light profile is closer to exponential ($n \approx 1$), and has not fully settled by the end of the simulation. This may be because the simulations continue to form stars despite supernovae (SNe) feedback. When star formation was (artificially) terminated after the coalescence of nuclei the light profiles were discovered to be more similar to a deVaucouleurs elliptical. This effect is also highly dependent on the initial gas fraction of the progenitor galaxies, with lower gas fractions having light profiles closer to a deVaucouleurs elliptical. If elliptical galaxies are common merger remnants, then these results imply that additional quenching mechanisms beyond our SNe feedback assumptions must exist. Additionally, the signal-to-noise ratio (S/N) was discovered to impact the measurement of the effective radius, with lower S/N tending towards smaller recovered radii, and that viewing inclination, specifically with respect to dust lanes, significantly affects recovered effective radius, and Sérsic index.

Key words: Galaxy: evolution, interactions, merger, morphology, structure, simulation.

1 INTRODUCTION

Understanding galaxy major mergers is a vital part of understanding galactic evolution. Through analysis of these mergers evidence has been discovered that the merger of two spiral galaxies can create elliptical galaxies (Toomre 1977). Numerical simulations demonstrate that major mergers (mergers with a mass ratio $\geq 1 : 3$) tend to result in the destruction of disk features and a loss of angular momentum in the gas (Barnes 1988; Hernquist 1992; Hopkins et al. 2008).

However, the remnants of simulated gas-rich galaxy major mergers can reform disk components and have ongoing star formation (Springel & Hernquist 2005; Cox et al. 2006, 2008; Lotz et al. 2008, 2010b,a). Simulations of major mergers between roughly equal mass disk galaxies tend to yield $r^{1/4}$-law mass profiles (Cox et al. 2008), implying elliptical morphologies. However, we must examine light rather than mass profiles to determine the observable morphology of merger remnants.

Light profiles are difficult to obtain from simulations
that only track mass (i.e., stars, dark matter, and gas) and do not calculate projected light or a galaxy’s spectral energy distribution. One may approximate observed morphologies directly from star particles, however this is only a reasonable approximation for older, gas poor galaxies such as in dry mergers (e.g. Bell et al. 2006; Conselice 2006). The observable appearance of gas-rich mergers is strongly affected by attenuation and scattering of light by dust (Jonnson et al. 2006). To accurately determine what a simulated galaxy would actually look like observationally, it is necessary to calculate how radiation interacts with dust. Simple dust screens do not produce accurate results when analyzing a galaxy due to the fact that the dust and stars are intermixed. Thus more complex methods are needed that take into account different geometries, scattering models and polychromatic information. One such code that does this is the Monte-Carlo radiative-transfer code, SUNRISE (Jonnson 2006; Jonnson, Groves & Cox 2010).

In this paper we focus our analysis on the morphology of a GADGET (Springel, Yoshida & White 2001; Springel 2005) N-body/hydrodynamical equal-mass gas-rich galaxy merger over time at different redshifts and signal-to-noise-ratios (S/N). Our technique is similar to other studies that have analyzed the observable morphology of galaxy merger simulations (e.g., Governato et al. 2009; Scannapieco et al. 2010; Wuyts et al. 2010). For comparison to observations at various redshifts and S/N we degraded these images, and analyzed the resulting images with Galfit (Peng et al. 2002). Additionally we analyzed comparable time steps from two other simulations to determine if our findings are valid for galaxies with different mass ratios and gas fractions

In section 2 we describe the GADGET galaxy models and the methods we used to degrade the images of the mergers that were produced by the SUNRISE. In section 3 we detail our use of Galfit and termination of star formation to analyze the galaxy mergers. In Section 4, we present the results of our analysis, and in Section 5 we discuss the implications of these results. Throughout this paper we assume a standard cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

## 2 METHODS

### 2.1 Galaxy Models

The simulations in this paper were created using the SPH code GADGET. The GADGET models include prescriptions for supernova feedback. We focused our analysis on a simulated prograde-prograde merger of two equal-mass Sbc galaxies with gas-fractions (fraction of baryonic mass that is gas) \( f_{\text{gas}} = 0.52 \). This merger simulation will be referred to as SbcPP (Cox et al. 2006, 2008; Lotz et al. 2008) for the rest of the paper; it follows the interactions of two galaxies until at time \( t = 1.76 \text{ Gyr} \) the galactic nuclei have coalesced and are no longer distinguishable. To see if trends found in this merger may apply to major mergers in general, we also analyzed remnants of two mergers with lower gas-fractions and unequal masses. The properties of these galaxies are given in Table 1. Each of these simulations has a resolution of \( 1.7 \times 10^7 \) particles per galaxy. We also analyzed the final time step of a simulation with properties identical to that of SbcPP but with ten times the particle resolution (\( 1.7 \times 10^8 \) particles per galaxy; SbcPP\( \times 10 \)).

### 2.2 Image Processing

The Monte-Carlo radiative-transfer code, SUNRISE, was used to calculate how the evolving stellar radiation interacts with absorbing and scattering dust particles. The metal density in the gas was used to calculate the dust densities, and the position of the star particles from the simulation were used as light sources. These calculations allow SUNRISE to create a multi-wavelength model of the simulated galaxy, which can be integrated over any arbitrary filter passband to produce images of the simulation with 11 isotropically positioned camera angles at several time steps. The SUNRISE images have no instrumental artifacts and no background sky noise; however, they do have particle noise from the original SPH models include prescriptions for supernova feedback. We focused our analysis on a simulated gas-fractions (fraction of baryonic mass that is gas) \( 52.05 \) because at this redshift the rest frame u-band peak shifts to approximately the center of the F814W filter used in the COSMOS survey. Using the ACS detector scale of \( 0.05 \text{ ”} \text{ pixel}^{-1} \) and angular size scale of 8.44 kpc arcsec\(^{-1} \) at \( z = 1.3 \), the correct re-bin scale is 43.5 pc pixel\(^{-1} \). We produced an ACS PSF for the F814W filter at the same native pixel scale for the detector using TinyTim\(^2\), and convolved the SUNRISE images with this PSF.

We then decreased the signal in the image to account for the cosmological \((1+z)^4\) surface brightness dimming in order to redshift the galaxy to \( z = 1.3 \). To determine the correct amount of noise to add, we made a mosaic of twelve relatively empty 200 by 200 pixel regions of a COSMOS image and calculated the standard deviation of the mosaic. This gave us an approximate Poisson sky background noise which was added to the surface brightness-dimmed images.

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1 Undegraded images of the simulations processed by Sunrise are available through the DIGGS database: http://archive.stsci.edu/prepds/diggs/

2 http://www.stsci.edu/software/tinytim/
We focus on time steps with \( t \geq 1.61 \) Gyr, which we refer to as the merger remnant. We allowed GALFIT to fit a single Sérscic component, convolved with the same PSF used to degrade the image, using the center of mass as our initial guess for the center of the Sérscic component. We then used the Sérscic index, \( n \), to determine the morphology of the merger remnant, with \( n = 1 \) corresponding to an exponential light profile (i.e. a late-type galaxy), and \( n = 4 \) corresponding to a deVaucouleurs light profile (i.e. an early-type galaxy). Additionally \( n = 2.5 \) is used as the division between early and late-type morphologies with early-type galaxies having \( n > 2.5 \).

For SbcPP we had four sets of images: un-degraded in both u-band and g-band, L08 (\( z = 0.01 \)), and ACS (\( z = 1.3 \)). We evaluated 11 camera angles and 14 time steps, from \( t = 1.61 \) Gyr (0.15 Gyr before coalescence of the nuclei) to 2.93 Gyr, for each of these image sets. To reduce the time it takes to analyze over 600 images we used parallel processing to run multiple fits at once. The errors estimated by GALFIT are calculated per pixel rather than per resolution element and therefore tend to underestimate the true error. Häussler et al. (2007) found that the distribution of errors given by GALFIT for a sample of simulated galaxies did not properly describe the true scatter in recovered morphological parameters. Using their analysis, we estimate that on average the GALFIT errors are underestimated by a factor of \( \sim 3 \) for both Sérscic index, \( n \), and effective radius. We apply this correction factor to the errors we get from GALFIT. We note, however, that the overall trends observed in our non-degraded datasets are much larger than the individual errors, even with this correction factor, and so our main results are not affected by this underestimation of the true error.

### 3 ANALYSIS

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### 3.1 Quenching Star Formation

The galaxy merger simulations presented in this paper have SNe feedback but contain no other means of terminating star formation (e.g. AGN feedback) other than extinguishing their gas supply. Due to the low number of bright, blue early-type galaxies in the local universe (e.g. Baldry et al. 2004), we expect that merger remnants must undergo some process that drastically reduces star formation, making the continuing star formation in simulated merger remnants unrealistic. This prompted us to analyze how quenching star formation affects the appearance of merger remnants. To accomplish this we used the SUNRISE code to artificially terminate all star-formation after the coalescence of the galactic nuclei by only calculating light produced from stars that were created up to the end of the coalescence. However, this still includes attenuation from dust in the gas. The mechanisms that quench star formation are also likely to expel gas and dust from the remnant. Therefore our method of turning off star formation without removing dust is not a perfect estimation of what a quenched galaxy would look like.

### 4 RESULTS

Figure 1 shows color composite images from every camera angle of the last time step in the SbcPP merger simulation 1.17 Gyr after the coalescence of nuclei. There is a dust lane which is very noticeable in camera angles 3, 4, and 6, and somewhat less noticeable in camera angle 5. Later in this section we discuss how this dust lane affects our data.

The typical galaxy magnitude for the ACS (\( z = 1.3 \)) simulated dataset in the F814W filter is \( m_{AB} \approx 24 \) at the end of the simulation (i.e. 1.17 Gyr after coalescence of the nuclei). The magnitude varies by \( \pm 0.5 \) magnitudes depending on camera angle, with edge-on inclinations fainter by 0.5 magnitudes and face-on inclinations brighter by 0.5 magnitudes.

By analyzing the un-degraded g-band images we determined the evolution of the circularized effective radius (equivalent to the radius at which half the light is enclosed, taking into account the observed axis ratio for each camera angle) over time (see Figure 2). Note that immediately after coalescence of the nuclei the effective radius increases, but as the remnant settles the effective radius slowly decreases until it reaches about 6.3 kpc at the end of the simulation. This radius is consistent with the effective radius of SDSS observed galaxies with similar baryonic mass (Shen et al. 2003). Figure 3 shows the evolution of Sérscic index over time for all four data sets (ACS, L08, un-degraded u and g-band). In each data set, except for ACS where the measurement errors are large, the Sérscic index continues to rise towards late times. We also compare the time evolution of effective radius for ACS and un-degraded u-band images by plotting them side-by-side (see Figure 4). The relation between the effective radius from the ACS and un-degraded u-band images indicates how S/N affects the measurement of effective radius which will be discussed later in this section.

### Table 1. Properties of simulated galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>( M_{tot} (M_\odot) )</th>
<th>( M_{bary} (M_\odot) )</th>
<th>( M_{disk}/M_{bulge} )</th>
<th>( f_{gas,a} )</th>
<th>( R_{disk,b} ) (kpc)</th>
<th>( R_{bulge,c} ) (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sbc</td>
<td>( 8.1 \times 10^{11} )</td>
<td>( 1.0 \times 10^{11} )</td>
<td>4.0</td>
<td>0.52</td>
<td>5.50</td>
<td>0.45</td>
</tr>
<tr>
<td>G3</td>
<td>( 1.2 \times 10^{12} )</td>
<td>( 6.2 \times 10^{11} )</td>
<td>4.6</td>
<td>0.19</td>
<td>2.85</td>
<td>0.62</td>
</tr>
<tr>
<td>G2</td>
<td>( 5.1 \times 10^{11} )</td>
<td>( 2.0 \times 10^{11} )</td>
<td>9.3</td>
<td>0.24</td>
<td>1.91</td>
<td>0.43</td>
</tr>
</tbody>
</table>

\( a \) Fraction of baryonic mass that is gas.

\( b \) Scale length of stellar disc.

\( c \) Scale length of stellar bulge.

For the rest of this paper these images will be referred to as the ACS images.
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Figure 1. SDSS g-r-i-band composite color images of the ShcPP merger remnant at the final time step of the simulation (1.17 Gyr after coalescence) from 11 different camera angles. The images are the un-degraded output from sunrise and have a resolution of 333 pc and a field of view of 100 kpc. The label in the upper-left corner of each image indicates the corresponding camera angle. At this time step, a dust lane is visible from camera angles 3-6, and an extended disk structure is evident in all camera angles. Additionally, the merger remnant retains tidal dwarfs, visible as bright blue spots in all camera angles.

4.1 Effect of Observational Conditions on Morphology

Our data from the un-degraded simulation, plotted in Figures 2-4, show that both the Sérsic index and measured effective radius are dependent on the observational conditions. First, the filter used to observe the galaxies makes a significant difference. In the last few time steps the g-band images have Sérsic indices 20% greater than the indices of the u-band images (Figure 3), but they have about the same effective radius (Figures 2 & 4). We also analyzed a few different camera angles in K-band over the same time frame of the merger simulation and found that these also have a larger Sérsic index and a larger effective radius than the u-band images indicating that the effects of dust are more prominent at shorter wavelengths, as expected, attenuating the brightness in the central regions which results in shallower surface brightness profiles. This effect contributes to the “morphological K-correction” that has been observed in a number of other studies (e.g., Bohlin et al. 1991; Giravalisco et al. 1996; Kuchinski et al. 2000, 2001; Windhorst et al. 2002; Papovich et al. 2003, 2005; Conselice, Rajgor & Myers 2008; Rawat, Wadadekar & De Mello 2009).

Galaxy inclinations (or equivalently camera angles for simulations) also affect the data. For instance the effective radius changes depending on the camera angle of the simulation (see Figure 2). In particular camera angle 3 (in which the dust lane is prominent) has significantly larger recovered effective radii than other camera angles in the later half of the simulation. There is also some effect on Sérsic index from different camera angles, which is due mostly to the placement of dust lanes. Cameras 3 through 6 show a nearly edge-on dust lane obscuring part of the galaxy (see Figure 1). These camera angles are outliers in much of the data and in most time steps they have significantly lower estimated Sérsic indices and have a greater variance in recovered Sérsic indices (see Figure 3). These effects are intensified when S/N is reduced.

Additionally we discovered that S/N and resolution impacts our measurement of the effective radius. At the end of the simulation our ACS images have a 30% smaller effective radius compared to the un-degraded images. In order to determine the cause of this difference, we isolated possible contributing factors (i.e., S/N and resolution) and examined the effect that each of them had on the resulting morphology independently. As a starting point, we assumed that pixel

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Figure 2. The evolution of effective radius from time $t=1.61$ Gyr (0.15 Gyr before coalescence of galactic nuclei) to 2.93 Gyr measured from the un-degraded g-band images from SUNRISE for the SbcPP merger simulation. Data from 11 camera angles and a weighted mean is plotted for each time step in a different color as shown in the legend of this figure. Errors on the weighted mean are derived from the dispersion of values for each camera angle at any given time step. The effective radius increases initially as the galaxies in the simulation undergo final coalescence of their nuclei and material is kicked out to large radii, after which the effective radius decreases steadily to late times. This decrease in effective radius with time is due both to stars settling into tighter orbits, as well as the passive fading of an extended stellar disk.

4.2 Comparison with Other Merger Simulations

The highest weighted Sérsic index for all of our data occurs in the last time step of the L08 images. The weighted mean Sérsic index for these data is $1.55 \pm 0.07$ (see Figure 3). This indicates that the galaxy merger presented in this paper does not produce a deVaucouleurs-elliptical light profile, although it does have a deVaucouleurs mass profile (Cox et al. 2008). However, at the end of the SbcPP simulation there is still an upward trend in the Sérsic index indicating that the remnants have not settled into their final morphological state 1.17 Gyr after the coalescence of the nuclei. In order to determine if this result is indicative of major mergers in general, we performed a similar analysis of the Sérsic index of other simulated major merger remnants. One
Figure 3. The evolution of Sérsic index for the merger remnant from time $t=1.86$ Gyr (0.1 Gyr after coalescence of the nuclei) to 2.93 Gyr. The camera angles and weighted mean follow the color scheme previously shown in Figure 2; errors on the weighted mean are given by the dispersion in Sérsic values for each camera angle at any given time step. Each panel shows results from a different realization of the same SbcPP simulation. From left to right: ACS rest-frame u-band images (weighted mean, only) degraded to a resolution of $\sim 800$ pc and cosmologically dimmed to a redshift of $z = 1.3$; un-degraded u-band images with a resolution of 333 pc; un-degraded g-band images with a resolution of 333 pc, and L08 g-band images degraded to a resolution of $\sim 400$ pc. The Sérsic index increases roughly monotonically through the end of the simulation for all realizations except the ACS images, implying that the remnant has not yet settled into its final morphological state. Furthermore, Sérsic index has a clear dependence on the observed wavelength for this simulation, with shorter wavelengths yielding smaller values of $n$ at all time steps.

Many works have found that high-redshift galaxies have significantly ($\gtrsim 30\%$) smaller effective radii than local galaxies, ranging to sizes $< 1$ kpc (Daddi et al. 2005; Trujillo et al. 2006a, 2007; van Dokkum et al. 2008). Our results indicate that systematic errors in determining effective radius due to S/N could account for this effect. We discuss this further in Section 5.

4.3 Star-formation Quenching

As stated in Section 3.1, these merger simulations lack sufficient mechanisms for quenching star formation, and based on the low number of bright blue galaxies in the local universe (Baldry et al. 2004) we expect that merger remnants must have some way to substantially reduce star formation. To approximate this, we used the SUNRISE code output excluding light from stars formed after the coalescence of galactic nuclei. These additional data (see Table 2) show that stars produced after the coalescence significantly affect the light profile. When we quench star formation, we increase the Sérsic index and the effective radius of the merger remnant, indicating that the light profile from young stars is more disk-like than that of older stars. This is expected as a star-forming disk is readily visible in the remnants from the original simulations (see Figure 1).
Morphologies of Simulated Galaxy Merger Remnants

Figure 4. The evolution of effective radius from 1.61 Gyr (0.15 Gyr before coalescence of nuclei) to 2.93 Gyr as derived from degraded and un-degraded u-band images. The color scheme is the same as in Figure 2 and errors on the weighted mean are given by the dispersion of values from 11 camera angles at each time step. The effective radius recovered from the degraded ACS images is roughly 30% smaller than the true effective radius measured from un-degraded images. This is largely a result of cosmological surface brightness dimming (see text for details).

Table 2. Results of major merger remnants analysis \( \approx 1.2 \) Gyr after coalescence

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Involved Galaxies</th>
<th>Mass Ratio</th>
<th>g-band ( R_e ) (kpc)</th>
<th>Sérsic Index</th>
<th>u-band ( R_e ) (kpc)</th>
<th>Sérsic Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SbcPP(^{a})</td>
<td>Sbc Sbc</td>
<td>1 : 1</td>
<td>1.47 ± 0.08</td>
<td>6.27 ± 0.26</td>
<td>1.19 ± 0.07</td>
<td>6.54 ± 0.30</td>
</tr>
<tr>
<td>SbcPP×10(^{b})</td>
<td>Sbc Sbc</td>
<td>1 : 1</td>
<td>1.89 ± 0.08</td>
<td>6.47 ± 0.33</td>
<td>1.68 ± 0.11</td>
<td>6.76 ± 0.32</td>
</tr>
<tr>
<td>G3PP</td>
<td>G3 G3</td>
<td>1 : 1</td>
<td>2.11 ± 0.16</td>
<td>5.06 ± 0.54</td>
<td>1.71 ± 0.13</td>
<td>4.91 ± 0.49</td>
</tr>
<tr>
<td>G3G2</td>
<td>G2 G3</td>
<td>1 : 3</td>
<td>1.68 ± 0.12</td>
<td>4.06 ± 0.13</td>
<td>1.41 ± 0.07</td>
<td>3.98 ± 0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Involved Galaxies</th>
<th>Mass Ratio</th>
<th>g-band ( R_e ) (kpc)</th>
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<th>Sérsic Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SbcPP(^{c})</td>
<td>Sbc Sbc</td>
<td>1 : 1</td>
<td>1.99 ± 0.59</td>
<td>6.85 ± 0.94</td>
<td>1.38 ± 0.56</td>
<td>7.70 ± 0.88</td>
</tr>
<tr>
<td>G3PP</td>
<td>G3 G3</td>
<td>1 : 1</td>
<td>3.11 ± 0.61</td>
<td>5.41 ± 0.67</td>
<td>2.67 ± 0.58</td>
<td>6.01 ± 0.68</td>
</tr>
<tr>
<td>G3G2</td>
<td>G2 G3</td>
<td>1 : 3</td>
<td>2.17 ± 0.48</td>
<td>4.28 ± 0.27</td>
<td>1.92 ± 0.37</td>
<td>4.70 ± 0.30</td>
</tr>
</tbody>
</table>

\(^{a}\) PP represents the prograde-prograde orbital direction for each galaxy in the merger simulation.

\(^{b}\) SbcPP simulation with 10 times the number of particles.

\(^{c}\) PP represents the prograde-prograde orbital direction for each galaxy in the merger simulation.
5 DISCUSSION

There are many papers which show that higher redshift galaxies appear to be smaller than their local counterparts (Daddi et al. 2003; Trujillo et al. 2006b,a, 2007; Toft et al. 2007; van Dokkum et al. 2008). It has been unclear how much S/N affects this finding. Some works claim that low S/N data make it virtually impossible to detect the low-surface-brightness outer regions of a galaxy, resulting in a profile that looks more centrally compact and underestimates the true effective radius (Mancini et al. 2010). However, other works claim that this size discrepancy is due mostly to an intrinsic difference in these high-redshift galaxies (Daddi et al. 2005; Trujillo et al. 2006b,a, 2007; Cimatti et al. 2008; van Dokkum et al. 2008). There is also likely some size evolution expected based purely on the assumption of a hierarchical cosmology. Bouwens & Silk (2002) have developed a theoretical scaling relationship of $R(z)/R(z = 0) = 1 - 0.27z$ for disk-like galaxies. For $z = 1.3$ this ratio is 0.65. Our data show that $R(z = 1.3)/R(z = 0) = 0.7$ which is due purely to S/N. The expected size relation at high redshift should be the product of both decreased S/N and intrinsic disk size-evolution, i.e., $R(z = 1.3)/R(z = 0) = 0.65$. Results from studies of high-z disk-like galaxies indicate a range of effective radii, ranging from about 0.3 - 0.7 times that of local galaxies for $1 < z < 1.5$ (Daddi et al. 2005; Trujillo et al. 2006b,a, 2007; Toft et al. 2007), and the mean ratio of effective radii of disk-like galaxies at $z = 1.25$ to local ones is $R(z = 1.25)/R(z = 0) \approx 0.6$ (Trujillo et al. 2007). This implies that S/N alone could explain why high-z galaxies appear compact.

Our Sérsic index data from the SbcPP simulation suggest that the remnant of this merger is a disk-like galaxy. However, Covington et al. (2010) studied the kinematics of this merger, and found that while the remnants have some rotational velocity, rotation is not the main mechanism of physical support. At the last step of the simulation $1.17 \text{Gyr}$ after the merger of nuclei, however, the value of the Sérsic index is increasing with time, indicating that the remnants have not settled into their final morphological state. Additionally, these remnants have some rotational velocity, however, rotation is not the main mechanism of physical support (Covington et al. 2010). This same property has been discovered in several high-redshift galaxies by Law et al. 2009. These findings suggest that galaxies with late-type morphologies that lack of rotational support may be good merger remnant candidates.

The cumulative data from all the simulations analyzed in this paper suggests that the final morphological state is highly dependent on the initial gas fraction of the progenitor galaxies with higher gas fractions yielding remnants with Sérsic indices closer to one. Additionally, quenching star formation after the coalescence of galactic nuclei increases the Sérsic index and the effective radius. This indicates that some mechanism must be responsible for quenching star formation in merger remnants in order to bring their light profiles into agreement with observations of typical massive, red-sequence galaxies. Consequently, this would make the light profile more similar to the mass profile.

Our results compare favorably with previous non-parametric studies of the morphologies of merger remnants from this SbcPP merger simulation (Lotz et al. 2008). Near the coalescence of the nuclei we discovered that a simple model consisting of a single Sérsic component does not produce a good fit and the galaxy merger looks highly irregular with large residuals. This is analogous to the Lotz et al. (2008) findings of disturbed morphologies during the same time period. We also find that at the end of the simulation, the merger remnants appear to be disk-like, with Sérsic index $n < 2.5$, consistent with their location on the Gini-M20 diagram in Lotz et al. (2008). Additionally the presence of dust lanes strongly affects both parametric and non-parametric measurements.

6 SUMMARY

We present a parametric morphological analysis of three GADGET galaxy mergers, with focus on the equal-mass prograde-prograde Sbc galaxy merger (SbcPP) simulation. The simulations have been processed though the Monte Carlo radiative-transfer code, SUNRISE, to generate the observable projected light. We degraded both the g-band and u-band outputs of SbcPP to simulate observations and ended up with four sets of data: un-degraded g-band, L08 images (g-band), un-degraded u-band, and ACS images (rest-frame u-band). We then used Galfit to fit one Sérsic component to each image.

(i) Our Sérsic index measurements of SbcPP indicate that the merger remnants remain disk-like though the end of the simulation 1.17 Gyr after the merger of nuclei. However, the value of the Sérsic index is increasing with time, indicating that the remnants have not settled into their final morphological state. Additionally, these remnants have some rotational velocity, however, rotation is not the main mechanism of physical support (Covington et al. 2010). This same property has been discovered in several high-redshift galaxies by Law et al. 2009. These findings suggest that galaxies with late-type morphologies that lack of rotational support may be good merger remnant candidates.

(ii) The final Sérsic index of a remnant is highly dependent on the initial gas fraction, with higher star formation rate (Lotz et al. 2010a) and higher gas fractions yielding more disk-like remnants.

(iii) We also found that quenching star formation increases the Sérsic index and the effective radius, indicating that the light profile of young stars is more disk-like than that of older stars. This also implies that some mechanism of quenching star formation is necessary to bring remnant light profiles into agreement with observations.

(iv) S/N impacts the measurement of the effective radius. The ACS images have a 30% smaller effective radius compared to the un-degraded images. Our data show that $R(z = 1.3)/R(z = 0) = 0.7$ which is due purely to observational effects. This is slightly above the observed size relation of 0.6 for galaxies with $n < 2.5$ at $z = 1.25$ discussed in Trujillo et al. (2007).

(v) g-band images have Sérsic indices 20% larger than the indices of the u-band images, but they have nearly the same effective radius. This is due to the fact that dust attenuation is highest in the central regions of the merger remnant and this attenuation is more severe at shorter wavelengths.

(vi) The inclination/camera angle has more of an effect on effective radius than on Sérsic index. However, the location of dust lanes has a significant systematic effect on

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effective radius and Sérsic index. Camera angles in which dust lanes are visible generally have significantly lower estimated Sérsic indices and a significantly larger effective radius. These camera angles also have a larger scatter in recovered Sérsic indices as compared to the other camera angles. These effects are amplified with decreasing S/N.

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