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The Evolution of Stellar Disk/Bulge Morphology after a Major Merger

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ABSTRACT

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1. INTRODUCTION

Galaxy mergers represent fundamental processes in the hierarchical structures in our universe. These gravitational interactions between two or more galaxies that eventually join into a single system and play crucial roles in shaping the dark matter halos and stellar distributions of the resulting galaxies. Particularly, dry mergers—interactions between gas-poor galaxies with minimal ongoing star formation—lead to distinct evolutionary pathways compared to their gas-rich counterparts (L. Lin et al. 2008). The merger process typically progresses through stages where galaxies initially develop tidal tails and bridges as they approach, followed by violent relaxation as their stellar and dark matter components mix, ultimately forming remnants that often resemble elliptical galaxies with characteristic surface brightness profiles (A. Toomre & J. Toomre 1972; C. J. Conselice 1997).

Understanding galaxy mergers is critical to our broader comprehension of galaxy evolution. A galaxy is defined as a gravitationally bound collection of stars, gas, dust, and dark matter that exists as an island in space, distinct from other similar collections (B. Willman & J. Strader 2012). Galaxy evolution refers to the processes through which galaxies form, grow, and change their properties over cosmic time, including their morphologies, stellar populations, and chemical compositions. Mergers fundamentally alter these evolutionary pathways by redistributing mass, triggering starbursts, fueling central supermassive black holes, and transforming morphologies from disk-dominated to spheroidal systems (J. E. Barnes & L. Hernquist 1992). The resulting changes in galaxy structure provide crucial observational signatures that allow us to reconstruct the assembly history of galaxies across cosmic time.

Current understanding of galaxy mergers has been significantly advanced through both observations and numerical simulations. Detailed simulations have revealed that the structural properties of merger remnants are strongly influenced by the initial mass ratio of the progenitor galaxies. As illustrated in Figure 1, there exists a clear relationship between merger mass ratios and the structural parameters of remnants, particularly their Sérsic indices and effective radii (T. Naab & I. Trujillo 2006). Equal-mass (major) mergers typically produce remnants with higher Sérsic indices ($n > 4$) characteristic of elliptical galaxies, while unequal-mass (minor) mergers tend to result in systems with lower Sérsic indices, often preserving disk components (F. Bournaud et al. 2005). The identification of merger signatures has been greatly enhanced through quantitative methods including the CAS (Concentration-Asymmetry-Smoothness) parameters (C. J. Conselice 2003), Gini/M20 coefficients (J. M. Lotz et al. 2004), and multi-mode statistics (P. E. Freeman et al. 2013).

Despite the importance of galaxy mergers in understanding galaxy evolution, there are still many open questions surrounding the galaxy-galaxy merger rate and its consequences. Theoretical and observational studies have yielded inconsistent results, with different groups and simulations producing varying estimates of the merger rate as a function of galaxy mass and merger mass ratio (e.g. S. Gottlober et al. (2001); T. Weinzirl et al. (2008)). Furthermore, the role of minor mergers versus major mergers in bulge formation remains a topic of debate, with some studies suggesting that minor mergers can be just as effective as major mergers in building bulge mass (T. J. Cox et al. 2008). The merger history of galaxies and how it affects their evolution is also not well understood, with many questions remaining about the typical merger history through which most of the bulge mass in the universe was assembled.

2. THIS PROJECT

In this paper, we will investigate how well the merger remnant from the specific case of a Milky Way-

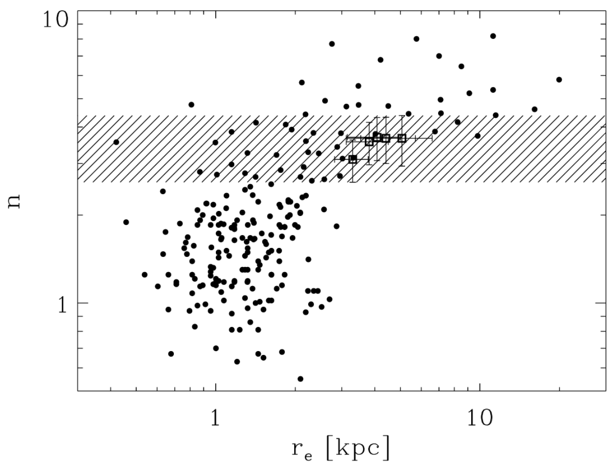

Figure 1. Distribution of effective radius versus Sérsic index for simulated merger remnants at different mass ratios compared with observed elliptical galaxies from T. Naab & I. Trujillo (2006). Symbols with error bars represent merger remnants from simulations with different mass ratios (1:1, 2:1, 3:1, and 4:1), while dots show observed elliptical galaxies from various surveys. The horizontal axis shows the Sérsic index n, and the vertical axis shows the effective radius in kpc. The simulations assume an initial disc scalelength of 3 kpc, though they are scale-free and can be shifted horizontally along the shaded area.

Andromeda (MW-M31) merger can be described as a classical elliptical galaxy by analyzing its surface density profile. Our focus is on determining the best-fit Sérsic profile for this particular post-merger system, which represents a realistic local example of a future dry galaxy merger. By fitting Sérsic profiles to this remnant's surface density profile, we will quantify how closely this specific merger product resembles a classical elliptical galaxy, typically characterized by Sérsic indices $n \sim 4$ and follows a de Vaucouleurs $R^{1/4}$ law.

This project directly addresses the open question identified in our introduction regarding how accurately merger remnants can be described as classical elliptical galaxies based on their surface density profiles. While previous studies have simulated generic galaxy mergers with varying mass ratios (T. Naab & I. Trujillo 2006; F. Bournaud et al. 2005), our work provides a case study of direct relevance to our Local Group. The MW-M31 system represents a nearly equal-mass merger (with mass ratio approximately 1:1.5) that is expected to occur in about 4-5 billion years (R. P. Van Der Marel et al. 2019), making it an ideal test case for theories of elliptical galaxy formation through major mergers. By focusing on this specific merger, we can assess whether real-world examples with realistic initial conditions follow the theoretical predictions that major dry mergers produce remnants with structural properties similar to classical ellipticals (P. F. Hopkins et al. 2010).

Understanding the structural outcome of the MW-M31 merger is particularly significant for our understanding of galaxy evolution. As the closest example of a future major merger, it serves as an important bridge between theoretical models and observable reality. If our simulated MW-M31 merger remnant closely follows the Sérsic profiles characteristic of observed elliptical galaxies (A. W. Graham & S. P. Driver 2005; J. Kormendy & R. Bender 2012), this would provide strong support for the major merger formation pathway for ellipticals.

3. METHODOLOGY

In this study, we utilize N-body simulations of the MW-M31 merger. N-body simulations are numerical algorithms that calculate the gravitational interactions between a large number of particles representing the mass distribution in galaxies, allowing us to model their dynamical evolution over time (W. Dehnen & J. Read 2011). In these simulations, both the MW and M31 are initially modeled with multiple components: a dark matter halo following a Navarro-Frenk-White (NFW) profile (J. F. Navarro et al. 1996), a stellar bulge, and a stellar disk.

Our analysis focuses on the simulation data described by (R. P. Van Der Marel et al. 2012), specifically examining the time period between 6.3 Gyr (snapshot 441) and 6.7 Gyr (snapshot 469) when the final merger occurs. We will use the highest resolution version of the simulation data (VHighRes) to ensure detailed structural analysis of the merger remnant. Our approach will focus primarily on the luminous components (disk and bulge particles) of both galaxies in snapshot 469, which represents a time shortly after the merger when the system has had sufficient time to undergo initial relaxation but before secular evolution significantly alters the structure.

We will combine the particles from the disk and bulge of both the MW and M31 using the high-resolution version of particle data (VHighRes), and calculate the surface density profile of the remnant galaxy using the surface mass density code from Lab 6. We will then assume that the remnant galaxy can be described by a Sérsic profile for an elliptical galaxy, given by the equation $I(r) = I_e \; e^{-7.67((r/R_e)^{1/n}-1)}$, and use the `scipy.optimize` module to fit the Sérsic profile to the surface density profile, estimating the best-fit parameters, including the effective radius R_e, the Sérsic index n, and the intensity I_e.

We expect to see a surface density profile as shown in Figure 2 and will fit the Sérsic index to the density profile.

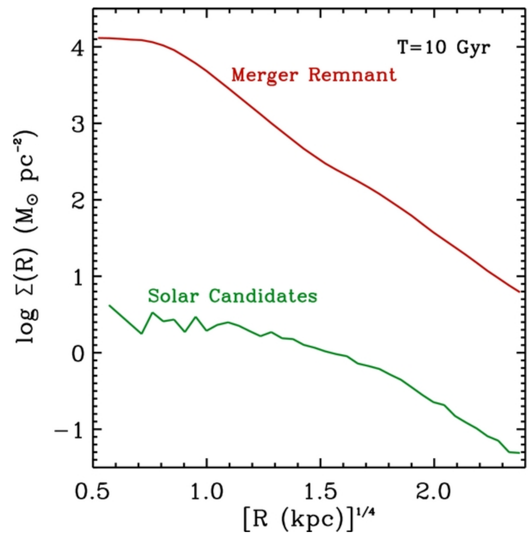

Figure 2. Adapted from R. P. Van Der Marel et al. (2012), this figure shows the projected surface-density profile (red) of luminous MW and M31 particles in the merger remnant at the end of the N-body simulation.

Based on our understanding of galaxy mergers and the formation of elliptical galaxies, we hypothesize that the remnant of the MW-M31 merger would be an elliptical galaxy and will be well-described by a Sérsic profile with a high Sérsic index ($n = 4$) following the de Vaucouleurs profile. Additionally, the simulated remnant galaxy is expected to have more radially extended than its progenitor galaxies. We predict that the effective radius (R_e) of the remnant galaxy will be larger than that of the individual progenitor galaxies, due to the increased size and scale of the merged system. Overall, our hypothesis is that the remnant galaxy will exhibit a density profile that is consistent with that of a classical elliptical galaxy, with a high Sérsic index, a large effective radius, and a surface-density profile that follows a de Vaucouleurs $R^{1/4}$ law.

4. RESULTS

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