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

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ABSTRACT

Major galaxy mergers are key drivers of the structural evolution of galaxies. They are a main process in the hierarchical model of galaxy evolution. They have a dramatic impact on galaxy structure through the disruption of stellar disks and the formation of spheroidal systems. In this work, we use high-resolution N-body simulations to study the structural outcome of a major dry merger. Specifically, we analyze whether the merger remnant can be accurately identified as a classical elliptical galaxy based on its surface mass density profile. We find that the merger remnant is well fit by a Sérsic profile of index $n = 4.05$, consistent with the de Vaucouleurs $R^{1/4}$ law, and also that this is confirmed independently by a χ^2 goodness-of-fit test with a best-fit value of $n = 4.07$. These findings are supportive of the hypothesis that large dry mergers produce elliptical-like remnants.

Keywords: Local Group (929) — Elliptical Galaxies (456) — Stellar disks (1594) — NFW Profile (1091) — Herquenist Profile

1. INTRODUCTION

Galaxy mergers represent fundamental processes in the hierarchical structures in our universe. They are gravitational interactions between two or more galaxies that ultimately merge as a single system and are directly responsible for playing significant roles in the dark matter halo formation and stellar structure of the resulting mergers. In particular, dry mergers, collisions between gas-poor galaxies with minimal ongoing star formation, yield various evolutionary tracks than 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 in our broader understanding of galaxy evolution. A galaxy is defined as a gravitationally bound system of stars, gas, dust, and dark matter that exist 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 constraints that allow us to reconstruct the assembly history of galaxies across cosmic time.

Our 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

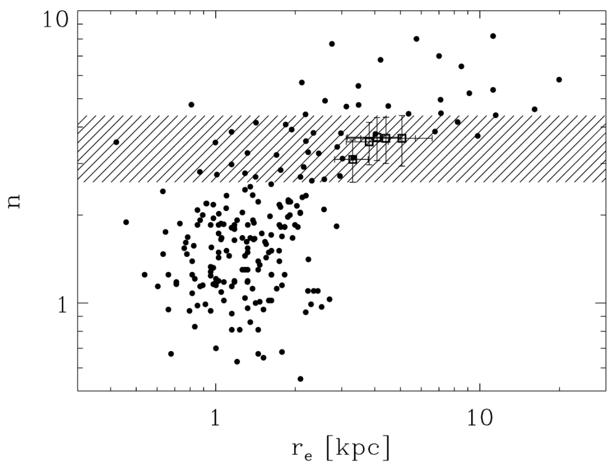

Figure 1. Distribution of effective radius versus Sérsic index for simulated merger remnants at different mass ratios compared with observed elliptical galaxies from T. Naab & I. Trujillo (2006). Symbols with error bars represent merger remnants from simulations with different mass ratios (1:1, 2:1, 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.

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 investigate how well the merger remnant from the specific case of a Milky Way-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 observations 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 low-resolution version of the simulation data (LowRes) to ensure detailed structural analysis of the merger remnant. We 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 LowRes data, and calculate the surface density profile of the remnant galaxy using the surface mass density code from Lab 6. 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 Sérsic index n.

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

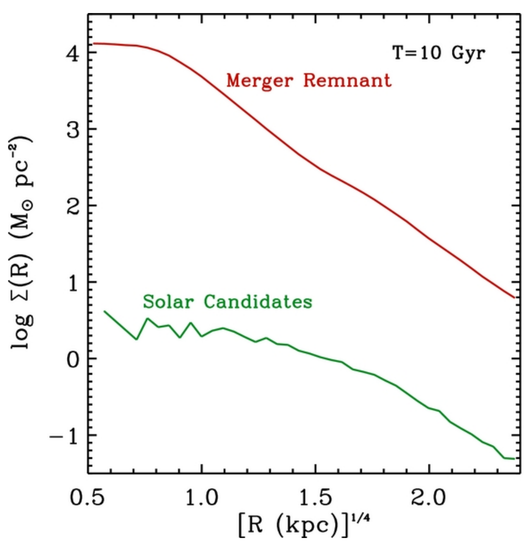

Figure 2. Adapted from R. P. Van Der Marel et al. (2012), this figure shows the projected surface-density profile (red) of luminous MW and M31 particles in the merger remnant at the end of the N-body simulation.

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

Figure 3 shows the logarithmic surface mass density profile of the remnant of the merger produced by combining the bulge and disk particles of both the MW and M31 galaxies from snapshot 469 of the simulation. The solid blue line represents the actual surface density profile extracted from the simulation data, while the dashed orange line shows the best-fitting Sérsic profile, obtained using a least-squares fit through ‘scipy.optimize.minimize‘. The best-fit Sérsic index was found to be $n = 4.05$. This close alignment between the simulated data and the fitted Sérsic curve indicates that the dry-merger remnant closely follows a de Vaucouleurs law.

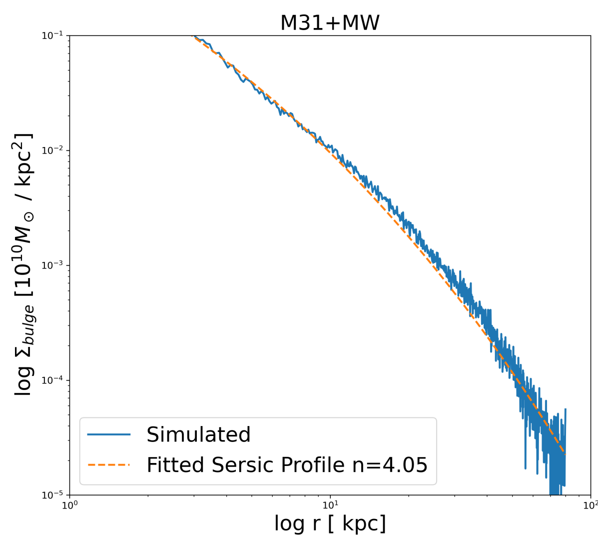

Figure 3. Logarithmic surface mass density as a function of logarithmic radial distance kpc for the buldge and disk components resulting from the merger of M31 and MW. The solid blue line represents the simulated surface density profile derived from the simulation data. The orange dashed line corresponds to the best-fitting Sersic profile with a Sersic index $n = 4.05$, obtained by minimizing the χ^2 deviation between the model and data.

Figure 4 presents the goodness of fit χ^2 as a function of the Sérsic index n. This plot was generated using a custom function we wrote to compute the total χ^2 between the surface density profile and the prediction of the model in a range of Sérsic indices. The curve clearly shows one of the minimums at $n = 4.05$, which corresponds to the best-fit profile shown in Figure 3. This local minimum in χ^2 confirms that the best match to the

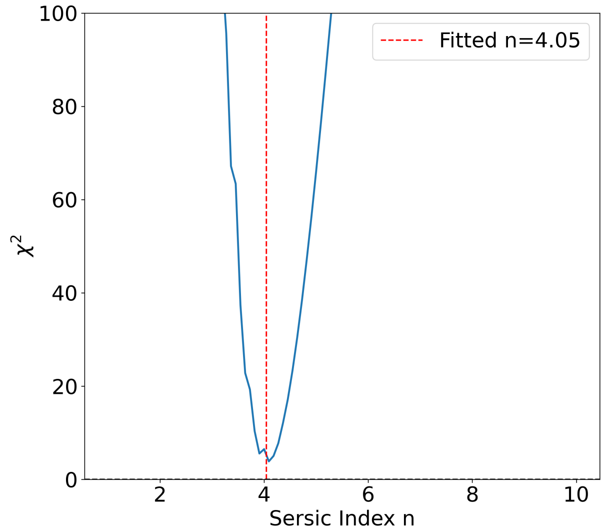

Figure 4. χ^2 goodness-of-fit as a function of the Sersic index n, used to quantify the deviation between the simulated surface density profile and a range of Sersic model profiles. The blue curve shows how χ^2 varies with different values of n. $n = 4.05$ is marked by a vertical red dashed line obtained from Figure 3. This minimum represents the best-fitting Sersic index for modeling the surface mass density profile.

simulated profile is a Sérsic function with a high index, consistent with the surface brightness profiles of classical elliptical galaxies. The minimum n of this method is $n = 4.07$, which is within the uncertainty of the code.

5. DISCUSSION

The first key result from our analysis is that the surface mass density profile of the simulated MW-M31 merger remnant is well fit by a Sérsic profile with an index of $n = 4.05$. This value is consistent with the de Vaucouleurs $R^{1/4}$ law, which describes classical elliptical galaxies. This outcome agrees with our original hypothesis that a major dry merger between two disk galaxies would result in a spheroidal remnant with a high Sérsic index.

The second key result is the minimum of the χ^2 distribution in $n = 4.07$, independently confirming that the Sérsic index obtained from 'scipy' is almost the best statistical match to the simulated surface density profile. This supports the robustness of our first finding by checking the rest of the n values.

These results align with the findings of previous studies (T. Naab & I. Trujillo 2006; P. F. Hopkins et al. 2010), which show that major mergers produce remnants with high Sérsic indices and large effective radii. Our result reinforces these conclusions by applying them to the M31-MW merger. Importantly, our result supports the major dry merger scenario as a viable pathway for the formation of elliptical galaxies.

Despite the strength of our findings, there was one main source of uncertainty. The Sérsic fitting process itself depends on initial parameter guesses and the the numerical stability of the optimizer, which may influence the exact best-fit index obtained. In order to mitigate the error and ensure numerical stability, we fit for n by taking the logarithm of the surface density profiles obtained after dividing by $10^{10} M_{\odot}/\mathrm{kpc}^2$.

6. CONCLUSIONS

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 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. These processes are central to our understanding of galaxy morphology transformation across cosmic time.

One key finding from our analysis is that the merger remnant of the MW-M31 system is well-described by a Sérsic profile with a best-fit index of $n = 4.05$. This high Sérsic index is consistent with a de Vaucouleurs $R^{1/4}$ law, which is characteristic of classical elliptical galaxies. This result directly supports our initial hypothesis that a major dry merger between two massive disk galaxies leads to a spheroidal remnant with elliptical-like structure.

A second significant result is that the χ^2 analysis independently confirmed the optimal Sérsic index to be $n = 4.07$, consistent with the fitted value from the surface density profile. This supports the robustness of the modeling and strengthens the conclusion that the MW-M31 remnant will structurally resemble an elliptical galaxy. This type of quantitative cross-validation is essential for testing theoretical predictions with simulation data.

Looking ahead, improvements could be made by incorporating baryonic physics like star formation and feedback, which were not fully modeled here. These factors could influence both the central structure and outer profile of the remnant.

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We respectfully acknowledge the University of Arizona is on the land and territories of In- digenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. The University strives to build sustainable relation- ships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

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