MNRAS **000**, 000–000 (0000) Preprint 7 May 2025 Compiled using MNRAS LaTeX style file v3.2

The Morphology of the MW-M31 Merger Remnant: Ending Shape

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May 7, 2025

ABSTRACT

Galaxies evolve in ways that alter their morphology, such as major mergers, which can transform spiral galaxies into elliptical galaxies. Understanding how these merged galaxy remnants settle, provide insight into galaxy evolution and the continuations of pre-merger structures. This study uses a high resolution N-body simulation of the Milky Way (MW) and Andromeda (M31) merger to study the final morphology of the remnant using isodensity contour analysis. Our goal is to determine whether the remnant exhibits a consistent elliptical classification across its radii, or if elongation happens in the outer radii possibly indicating structures of the pre-merger disks. Findings show that in the inner regions (<20 kpc), the remnant is nearly spherical with axis ratios between 0.87-0.94 (E1 classification), the outer regions (>20 kpc) are more elongated, with axis ratios ranging from 0.59-0.86 (E3-E2 classification), indicating a complex structure with radius dependent features. Notably, from 600 Gyr to 700 Gyr, the outer regions (beyond 50 kpc) showed a decrease in elongation, with axis ratios increasing by 0.05-0.1, indicating a relaxation process over time. This suggests that merger remnants can exhibit varying degrees of relaxation depending on both radius and time, providing clues about the galaxy's merger history.

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Key words: Major Merger – Spiral Galaxy – Elliptical Galaxy – Triaxial – Isodensity Contours

1 INTRODUCTION

Galaxies come in all shapes and sizes, from flat rotating disks to unstructured spheroids. One of the most dramatic drivers of galaxy shape evolution is a **Major Merger**, which is when two galaxies of similar mass collide into each other and form a new merged galaxy. The Andromeda galaxy (M31) and the Milky Way (MW) are two galaxies inside the **Local Group**. The Local Group is a collection of galaxies, mostly dwarf galaxies, that are gravitationally bound together. Both the Milky Way and Andromeda are classified as **Spiral Galaxies**, characterized by the flat rotating stellar disk, with distinct arms that twirl around the center. Simulations predict that these two galaxies will merge in the next several billion years, forming a single, more massive remnant called an **Elliptical Galaxy**. Elliptical galaxies exhibit less structure, with stars moving in random orbits, forming oval or spherical shapes. The MW-M31 merger is a unique opportunity to study the internal structure of an Elliptical galaxy once it reaches an equilibrium point, specifically if its shape and classification vary with radius. One method of assessing this transformation is looking at the stellar density via **Isodensity Contours**, which mark regions of equal density, and are a method to assess morphological changes and identify structural consistency across radii.

A **galaxy**, as defined by Willman & Strader (2012), is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons (gas, dust, and stars) and Newton's laws of gravity. **Galaxy Evolution** refers to how galaxies and their components develop over cosmic time. These transformations include internal mechanisms like star formation and external gravity interactions like mergers, accretion, and tidal stripping. Studying major mergers is critical in recognizing the evolution of a galaxies life, which helps us understand the history of our universe based on observable galaxies. The MW-M31 system is useful for this because we can study the detailed evolution of two spiral galaxies undergoing a major merger, including how mass, angular momentum, and morphology evolve during and after the collision.

Research has shown the main ways elliptical galaxies form are from major mergers between spiral galaxies. Barnes & Hernquist (1992) showed through simulation that when two disk galaxies merge in a roughly head on orbit a violent randomization of orbits happen, which results in an elliptical system. The final morphology depends on several factors; mass ratios, starting orbital angular momentum, dust content, dark matter mass, and the presence of a pre-existing bulge. It is important to note that galaxies undergoing mergers are often irregular, as illustrated in Figure 1. Isodensity mapping is essential to understanding how merged galaxies settle, and allow us to classify the final morphology shape.

There are many questions in our understanding of galaxy formation through mergers. A key one is whether the merger remnant will relax into a sphere, or if it retains elongations that reflect pieces of the previous galaxy. Barnes & Hernquist (1992, p. 724-725) ran N-body simulations and found that disk galaxies only form elliptical cores if the galaxies have pre-existing bulges and if they were head on collisions, while inclined encounters create flattened remnants. Another question is if we can see structures from the individual

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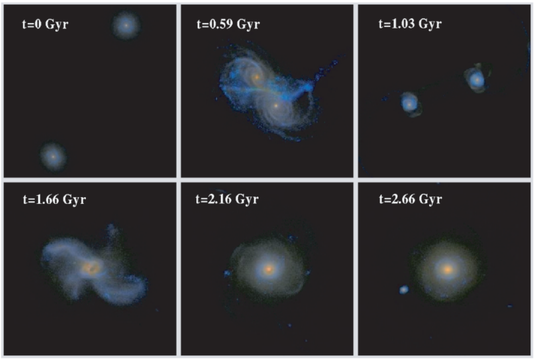
[h] 

Figure 1. Evolution of simulation of a major galaxy merger. The time displayed in each image is the evolution of the system from the start of the simulation. The top row shows the pre-merger galaxies with a pass by, and the bottom row shows when the merger forms a center nuclei with large features that still represent the two seperate galaxies. Which then settles into the final elliptical remnant form. The field of view for t=0 & t=1.03 Gyr is 200 kpc, while the rest are 100 kpc. The blue represents star forming regions, tidal tails, and outer regions. Red represents dust-enshrouded star-forming nuclei. Lotz et al. (2008).

galaxies, do those structures appear throughout the full galaxy, or does proximity to the center of the merger affect that? The findings in **?**, p. 13 saw the inner regions of a remnant looked spherical, while the outer contours had features of previous galaxies such as the shell and tails. The third question is how does the gas content, Wet (gas-rich) or Dry (gas-poor), of a galaxy influence the final structure of the merger? While comparing wet and dry merger simulations,(Lin et al. 2010, p. 12) found that dry mergers produced boxy and slow rotating galaxies, hinting that wet mergers appear different, suggesting that gas can be behind the final shape of a merger remnant.

2 PROPOSAL

2.1 This Project

This project examines the final morphology of the MW-M31 merger remnant, assessing whether its shape is spherical or elongated using Hubble's E0-Ey classification. The focus is on whether classification varies with radius, indicating structural chages. I will generate density maps in three planes, fit ellipses to isodensity contours, and assign E-types at different radii.

This project also examines how remnant structures evolve over time. Prior simulates (e.g., **?**, PDF p. 16) suggest that even 10 Gyr post-merger, outer regions may retain shells while inner regions relax. By analyzing changes in axis ratio and ellipticity across radii, I will asses whether a single Hubble classification can adequately describe the entire remnant, and if that classification would change over time.

Understanding how merger remnants settle, whether they relax into spheroids or retain elongated structures from pre-merger galaxies, is crucial for studying galaxy evolution. Major mergers are key in transforming spiral galaxies into spheroids, but if structural irregularities persist at specific radii, the assumption that all remnants become spherical may be oversimplified. Examining radial variations in shape and elongation can refine galaxy classification and reveal how long merger signatures persist, aiding in reconstructing merger histories.

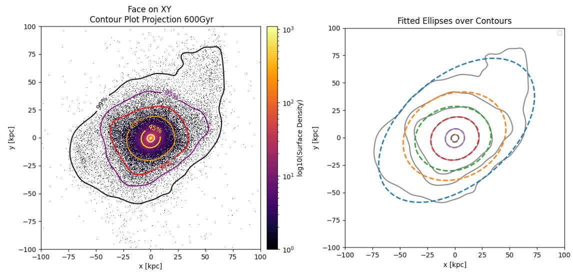


Figure 2. Methodological overview. The simulated merger remnant was center and rotated to view a straight on view of the XY plane. The 2D surface density was computed and isodensity contours at varying density percentages were extracted. Ellipses were fit to each contour level. This graph sees both the true shapes at increasing radii, and the averaged ellipse of the shape to estimate the Ellipticity at different radii. Shown is the XY Plane or Face-on View of the remnant at 600 Gyrs.

2.2 Methods

This project uses the Van der Marel et al. (2012a); **?** MW-M31 merger simulation to analyze the final stellar morphology of the merger remnant. The simulation was conducted with an N-body simulation, where in each mass element (particles representing a stellar star) undergo gravity interactions with the other particles over time. Each galaxy is modeled with a combination of a dark matter halo, a stellar disk, and central bulge. For this simulation I focused on the stellar components in the galaxies, particles in the disk (type 2) and the bulge (type 3), to isolate the observable galaxy.

The simulation uses the high-resolution MW and M31 dataset. A comparison between snapshots 5-7 Gyr (snapshot 500, 600, 700), was chosen because this was after the galaxies had merged and relaxed. Using my own Python implementation, I first merge the stellar particles from both galaxies into a single data file. Next, I compute the total mass-weighted center of mass (COM) position and velocity using `CenterofMass.py`, of the bulk and disk particles. The analysis is carried out in units of kpc and km/s.

After centering the system, I compute the angular momentum vector of the remnant using:

$$\mathbf{L} = \sum_i m_i (\mathbf{r}_i \times \mathbf{v}_i)$$

where m_i is the mass of particle i, $\mathbf{r}_i$ is its position relative to the center of mass, and $\mathbf{v}_i$ is its velocity. To orient the galaxy for a face on view, I calculated the angular momentum vector and see how much it angles from the Z-axis. A skew-symmetric matrix is constructed $\mathbf{K}$ from the rotation axis and apply the rotation matrix:

$$\mathbf{R} = \mathbf{I} + \mathbf{K} + \mathbf{K}^2 \cdot \left(\frac{1 - \cos\theta}{\sin^2\theta} \right)$$

where $\mathbf{I}$ is the identity matrix and θ is the angle between $\hat{\mathbf{L}}$ and $\hat{\mathbf{z}}$. This realigns all particle positions and velocities so that the disk lies in the XY plane.

The surface density is computed in each 2D plane using a weighted histogram of particle positions:

$$\Sigma(R) = \frac{\sum m_i}{A}$$

where m_i are the masses of the particles within each bin of area A, and $\Sigma(R)$ is the resulting surface density. First I construct the iso-density contour over the density maps corresponding to fixed confidence levels (e.g., 40%, 65%, 90%, 99%), the contours as smoothed with a gaussian function to eliminate small fluctuations in shape. Each contour is then fit with an ellipse using `EllipseModel()` from `skimage.measure`, and the axis ratio is computed for each level:

$$\frac{b}{a}$$

The Hubble E-type classification (E0-E7) is then assigned to each contour based on:

$$E = \mathrm{int}(10 \times (1 - b/a))$$

It is then time to see if the remnant is spherical, elongated, or traixial and how this varies with radius. I generate three plots:

- **2D Surface Density Maps (XY, XZ, YZ):** These face-on, top-down, and side-view projections show the distribution of stellar mass. By visually comparing the shape of the remnant in all three planes, I can identify signs of elongation, flattening, or any other types of distortions that deviate from a spherical shape.
- **Isodensity Contours with Ellipse Overlays:** Isodensity contours show enclosed density where a certain percentage of stellar mass resides, e.i. contour 60 is where 60% of the galaxy resides in. These contours allow me to see how the shape changes at different radii, since each confidence level ends up being at its own distance. Circular contours indicate spheroidal symmetry, while elongated ellipses suggest triaxiality.
- **Grouped Bar Chart of b/a vs Radius with E-Types:** This summary plot visualizes how the axis ratio b/a, which is a direct measurement of flattening, varies with radius in each projection. By using these axis ratios to find the Hubble E-types at each contour, I can see if the galaxy has a consistent morphological class throughout or if it changes with increasing radius. This plot answers the core question of my project: does the remnant exhibit different structural classifications at different radii?

3 RESULTS

3.1 Projected Density and Ellipse Fits at 700 Gyr

Figure 3 shows the projected 2D surface density of the merger remnant at 700 Gyr in the XY (face-on), XZ (top-down), and YZ (side) planes. For each plane, the left panels show the smoothed surface density with confidence level contours which encapsulates a total percentage of the galaxy. The confidence levels shown are 10% 45%, 80%, 90%, 95%, 99% which were chosen because the majority of the radii increased 10 kpc. This allows us to compare the symmetry and of the remnant as a function of radius. The right panels show ellipses fitted to those contours using a custom function that finds the largest contour and fits an ellipse to it. The ellipse function contains information such as ellipse origin, major (a) and semi major (b) axes sizes, etc. We have another step of comparison by places all 3 planes next to each other to give us a view of the 3D remnant. A spherical remnant would appear uniform across all planes, but the remnant appears more spherical in the XY plane and more elongated in the others.

3.2 Axis Ratio Evolution from 600 to 700 Gyr

Figure 5 compares the axis ratios b/a of ellipses fitted at the various average radii for two different times: 600 Gyr and 700 Gyr. This was generated using a custom grouped bar plot function that displays the XY, XZ, and YZ projections side by side, and each bar labeled by its corresponding ellipse E-type (E0–E7). The central region of the remnant are highly spherical in all projects with their classifications around E1 (0.87 and 0.94 axis ratio). At larger radii the ellipses become more elongated falling into the E2/E3 range (0.59-0.86 axis ratio). This stretching could in fact be structures still in tact from the previous galaxy. From 600 Gyr to 700 Gyr, outer regions show an increase in (b/a) by 0.05-0.1, indicating relaxation. All of this together suggests while inner regions of the galaxy become spherical (E0–E1), there is structure and elongation in the outer radii, but those structures tend to relax over time.

4 DISCUSSION

One of the key results from the previous section is the trend in axis ratio (b/a) with radius and projection plane. The remnant appears nearly spherical in the central regions across all planes (E1), but becomes progressively elongated (E2–E3) in the outer regions. The results support the hypothesis that inner stars lose disk memory due to gravitational chaos, while outer stars may retain pre-merger structures.

My result is consistent with previous literature on galaxy mergers. For example, **?** and **?** show that violent interactions during major mergers redistribute stellar orbits, leading to a bulged or spheroid central structure. The outer regions are less affected by gravitational interactions and may retain tidal features, shells, or remnants of spiral arms (**?**). The significance of this result is that it supports the idea that the morphology of a merger has radius-dependent features. Outer structures can retain clues about a galaxies pre-merger identity, and that those features can become less prominent over time. This means that a merged remnant trends towards a spheroid shape the longer it exists. This can give us a new way to estimate ages of galaxies and give us clues about the galaxies pre-merger identities.

Key uncertainties include the absence of dark matter and gas in the simulation, which may affect shape stability in the outer regions. Additionally, I did not account for dust regions that could contribute to star formation during or after the merger. New stars could introduce additional gravitation interactions, further changing the remnants morphology over time. Lastly, by choosing a large snapshot spacing (600 to 700 Gyr) I may be missing short-time scale variations or substructures that may appear due to the merger, and in fact what we may see is not elongation from the previous galaxies structures.

5 CONCLUSION

Galaxies transform through mergers, reshaping structured galaxies such as spirals into elliptical or spheroidal remnants. Understanding how these merged galaxy remnants settle provides insight into galaxy evolution and the continuations of pre-merger structures. This study uses a high resolution N-body simulation of the Milky Way (MW) and Andromeda (M31) merger to study the final morphology of the remnant using isodensity contour analysis.

The goal was to determine whether the remnant exhibits a consistent elliptical classification across its radii, or if elongation occurs in the outer regions, possibly indicating the persistence of pre-merger structures. Findings show at inner regions <20 kpc, the remnant is nearly spherical with axis ratios between 0.87 and 0.94 (E1 classification), and outer regions >20 kpc are stretched with axis ratios between 0.59 and 0.86 (E3-E2 classification), indicating a complex structure with radius-dependent features. This finding aligns with

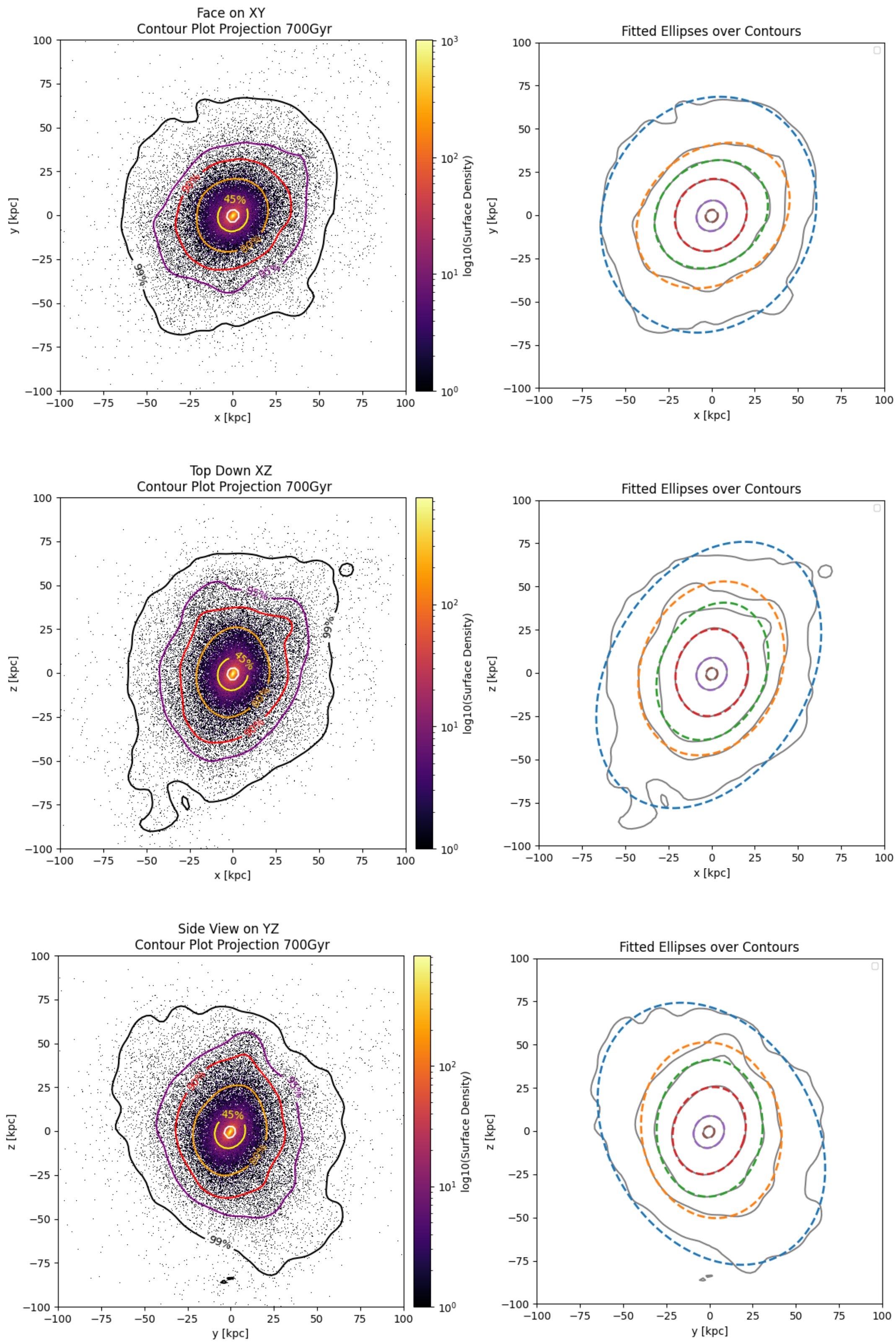


Figure 3. Surface Density and Ellipse Fits for the Remnant at 700 Gyr. Each row shows a 2D projection of the system: XY (top), XZ (middle), and YZ (bottom). Left: Smoothed surface density maps with overlaid confidence-level contours, where the colorbar shows $\log_{10}$(surface density). Right: Ellipses fitted to the contours from the left panel, color-coded by contour level. Axis labels are in kpc. *T*he remnant becomes increasingly elongated with radius.

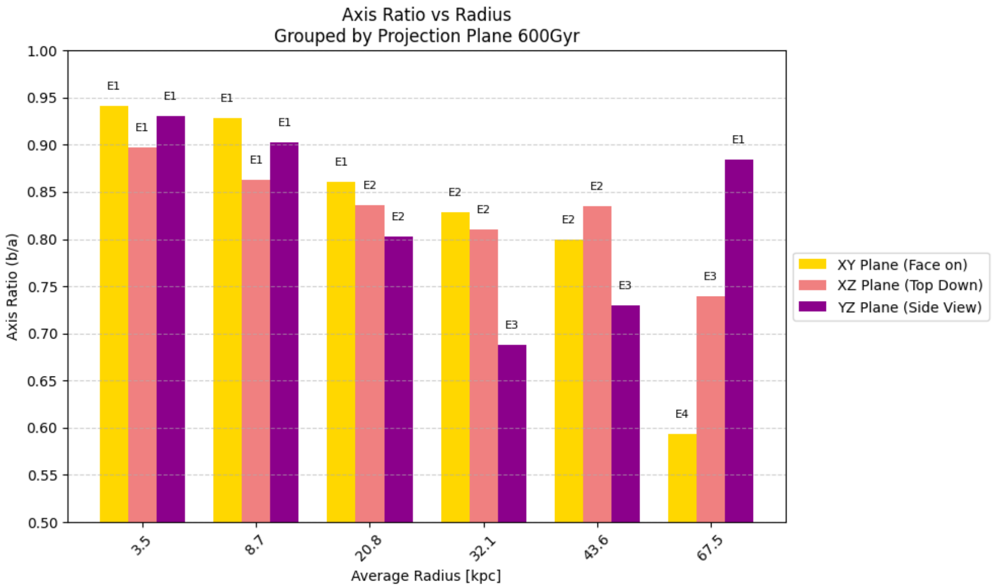


Figure 4. Axis Ratio b/a vs. Radius for 600 Gyr Each bar represents the axis ratio of a fitted ellipse in a given projection plane: XY (gold), XZ (pink), and YZ (purple). Bars are grouped by average radius (x-axis), and labeled by E-type classification (E0–E7) based on b/a values. Outer radii show elongation with higher E-type classifications ranging from E4-E2. There is not a consistent shape with the planes at higher radius which is to be expected for stretching and elongated structures.

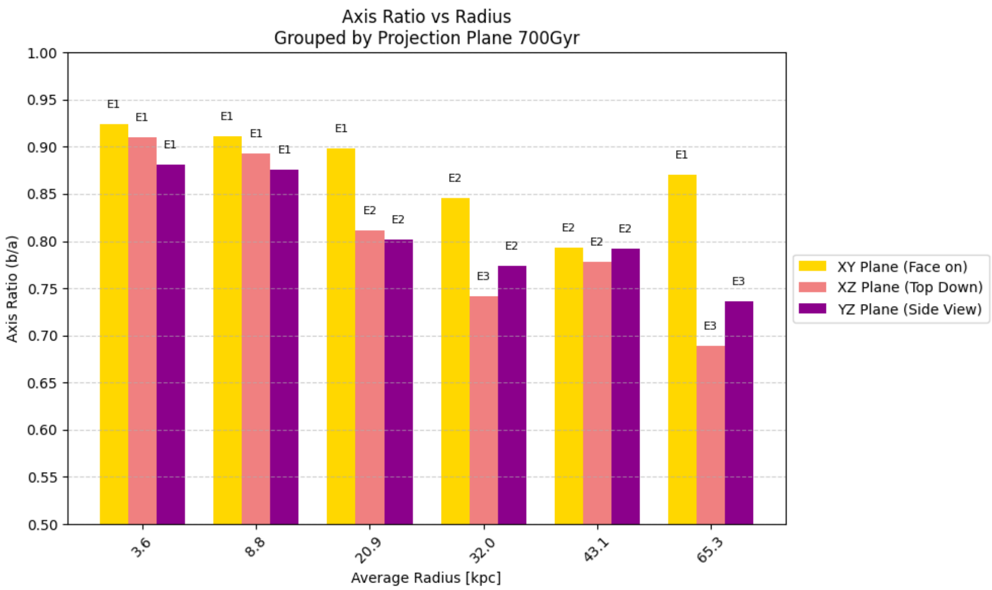


Figure 5. Axis Ratio b/a vs. Radius for 700 Gyr Each bar represents the axis ratio of a fitted ellipse in a given projection plane: XY (gold), XZ (pink), and YZ (purple). Bars are grouped by average radius (x-axis), and labeled by E-type classification (E0–E7) based on b/a values. The outer radii still follow the trend of elongation, but have relaxed towards a spherical shape. Instead of seeing E-types of E4-E2, we now only have E3-E2, and the difference in the axis ratios between planes at the same radii has also decreased.

previous work by Barnes and Hernquist (1992), who noted that outer regions can retain disk-like features even after significant interactions. This outcome suggests that outer stellar structures preserve some memory of pre-merger configurations, potentially affecting the morphology classification of merger remnants.

Furthermore, when comparing 600 Gyr to 700 Gyr, the change in shape of the outer regions showed a measurable decrease in elongation, with the axis ratios increasing by 0.05-0.1, suggesting a gradual relaxation process over time. Future work should incorporate dark-matter and gas components to assess their influence on shape relaxation and structural persistence. Additionally, analyzing smaller time steps within the simulation could reveal transient features that may contribute to the observed elongations.

ACKNOWLEDGMENTS

This work utilized the following software packages: numpy (van der Walt et al., 2011), matplotlib (Hunter, 2007), scipy (Jones et al., 2001–), astropy (Astropy Collaboration et al., 2013), and ipython (Perez & Granger, 2007, DOI: 10.1109/MCSE.2007.53). Some of the code development was supported by OpenAI's ChatGPT including functions for data merging, ellipses fitting, and providing structural and formatting critique on this report. This project was supported by resources and feedback from the Astronomy Department at the University of Arizona. Additionally, we acknowledge the land and territories of the O'odham and Yaqui peoples, on which the University of Arizona is situated.

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