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

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The **Stellar Disk** The first time a keyword appears in main text bold it A **Major Merger** or define with equation

1 INTRODUCTION

Galaxies come in all shapes and sizes, from flat rotating disks with spiral arms to massive 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 vast region of space where many galaxies, mostly dwarf galaxies, 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 show less structure than spiral galaxies, and the stars orbit in random paths, creating shapes that look like ovals or spheres. 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 are lines on a map that mark off regions of equal density. Isodensity contours allow us to visualize the spatial distribution of structures so that we can infer whether the galaxy is spherical, oblong, or **triaxal**, and if these shapes are consistent at different radii.

A **galaxy**, as defined by **?**, 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 lead to us understand the history of our universe based on the galaxies we can observe. 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.

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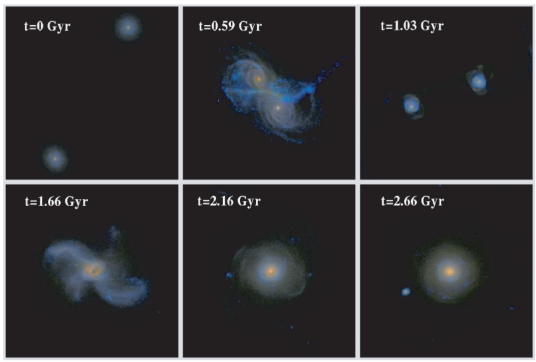

Figure 1. Evolution of simulation of a major galaxy merger. The time displayed in each image is the evolution of the system from the start of the simulation. The top row shows the pre-merger galaxies with a pass by, and the bottom row shows when the merger forms a nuclei and settles into the final remnant 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).

Research has shown that the main way elliptical galaxies form are from major mergers between spiral galaxies. **?** 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 or spheroidal 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 in the process of merging are irregular, as illustrated in Figure 1. Isodensity mapping is essential to understanding how merged galaxies settle, and classifying the final morphology shape.

Studying galaxy mergers is critical in understand how galaxies grow and evolve. Numerous simulations predict the MW-M31 merger will evolve into an elliptical galaxy; Barns & Hernquist state that for that to happen the merger would be nearly head on, violent, and both galaxies would need a large pre-existing bulge (722-724). Elliptical galaxies can take on shapes such as spherical, elliptical, or triaxial, it depends on the merger history, the mass ratios, dark matter mass, dust content, starting orbital parameters, etc. Another thing to consider is the time scale, freshly merged galaxies may appear irregular before settling into a elliptical shape, see Figure 1. By categorizing the shapes of galaxies, and running simulations on mergers we can predict if a galaxy is newly formed, has satellites, has merged before. Once we know the evolution of galaxies we can look at the distribution of galaxies across the universe and see if there are pools of activity, or one side of the universe has more activity, etc.

The current understanding of galaxy evolution is that major mergers between spiral galaxies are the primary way elliptical galaxies are created. A general picture is that once the galaxies are in gravitational range, tidal interactions happen that throw stars into random orbits, and this creates tails and bulges. Gravity pulls the center of the two galaxies together in a spring-like fashion until the centers are merged. Since the stars have taken on random orbits they create a giant spherical cloud around the center of mass, or an elliptical galaxy. Sometimes the galaxy shape is elongated or triaxial, meaning that there are still substructures present from the original disks. Formed structures also depend on whether it was a dry merger (galaxies with little gas) or a wet merger (gas-rich galaxies). With a gas-rich galaxy star formation can begin and new structures can be created.

Despite the progress in understanding mergers, several questions remain regarding the final morphology of the MW-M31 merger. Will the remnant for a classical Hubble classification elliptical galaxy (E0-E7)? Will the galaxy exhibit elongations or triaxial characteristics? How does the shape vary as a function of the radius? Would the inner region act more spherical while the outer region shows underlying structures from the parent galaxies? Furthermore, would this merger be classified as wet or dry, and how does the remnant behave in terms of star formation? This paper focuses on the question of what shape the remnant takes, whether it is a traditional classification, and how the shape varies by radius. By addressing this question the project will help contribute understanding of mergers and how they reshape galactic structures.

2 PROPOSAL

2.1 This Proposal

This research aims to determine whether the MW-M31 merger remnant is a spheroid or exhibits elongation/triaxiality. Additionally, I will classify its Hubble type (E0, E7, S0) based on its shape and analyze whether its morphology varies with radius.

2.2 Methods

I will use the van der Marel et al. (2012) simulation snapshots post-merger to analyze the stellar component of the remnant. I'll want to run a simulation with current stellar data points from the MW-M31 (not halo or dark matter), then analyze snapshots that happen when the simulation reaches equilibrium, probably a few Gyrs. The flow of work will be as follows:

2.2.1 Identify Relevant Snapshots and Particles

- Use the MW and M31 data sets provided in class
- ReadFile.py to load simulation
- GalaxyMass.py to get total mass of particle type (stellar for this project)

2.2.2 Centering and Aligning the Remnant

- Determine COM position and velocity using CenterofMass.py

$$\mathbf{r}_{\mathrm{COM}} = \frac{\sum m_i \mathbf{r}_i}{\sum m_i}$$

- Run OrbitCOM.py to generate time simulation of merger, get snapshots of a few Gyrs
- Align the total angular momentum vector ($\mathbf{L}$) with the z-axis to view galaxy face on or edge on (Lab 7)

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

2.2.3 Visualizing Shape of Remnant

Generate various plots to see the structure of the merged galaxy, snapshots should be aged a few Gyrs.

- Disk Density Plot both edge-on and face-on by using 2D histograms.

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

where $\Sigma(R)$ is the surface density at radius R, m_i are the masses of the particles, and A is the area of the bin.

- Velocity scatter plot both edge-on and face-on to see if there are any patterns in rotation.

$$v_{\tan} = \arctan\left(\frac{v_y}{v_x}\right)$$

where $v_{\tan}$ is the tangential velocity derived from the velocity components.

- Plot radial distribution of stars to see how density of stars vary with radius. Recognize if shape is spherical, triaxial, elongated, has tidal tails, or spiral arms.

$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM}{dr}$$

where $\rho(r)$ is the density profile and $\frac{dM}{dr}$ represents the mass enclosed in spherical shells.

- Plot radial velocity distribution to further distinguish between disk-like or elliptical structure.

$$v_{\mathrm{rad}} = \frac{x v_x + y v_y}{\sqrt{x^2 + y^2}}$$

where v_{rad} represents the radial velocity component.

- Use MassProfile.py to compute the enclosed mass and circular velocity as a function of radius.

$$v_{\mathrm{circ}} = \sqrt{\frac{GM(r)}{r}}$$

where v_{circ} is the circular velocity, G is the gravitational constant, and $M(r)$ is the enclosed mass at radius r.

2.3 Hypothesis

My hypothesis is that the MW-M31 merger remnant will form a triaxial elliptical galaxy rather than a perfect spheroid. This is because both galaxy are large 1×10^5 ly 2.6×10^5 ly, and are spiral galaxies with halos in the center on trajectory for a head on collision. I expect the center of the remnant to be rather spherical with the edges showing remnants of structure.

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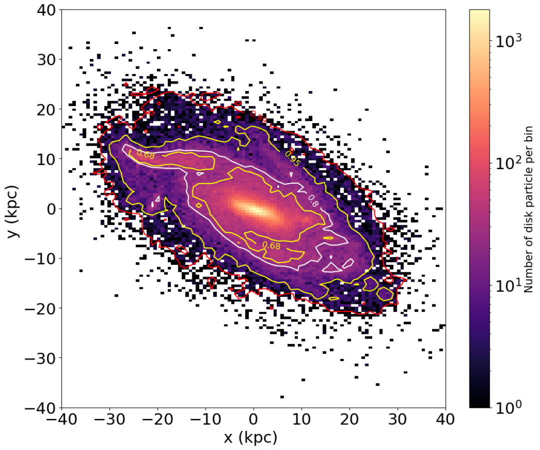

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Figure 2. Methodology: example of a face on density plot of M31, generated in Lab7.

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