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Effects of Component Galaxies on M31-Mw Remnant Final Structure

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ABSTRACT
As Galaxies merge they create

Key words: Major Merger – Oblate/Prolate/Triaxial – Ellipticity – Dark Matter Halo – Halo Shape

1 INTRODUCTION

Our universe is composed of stars, most of which are bound together her and act is ways Newton's laws and baryons (gas, dust and stars) cannot describeWillman & Strader (2012). These clusters of stars are called **galaxies**. Over time these **galaxies evolve** rotating, collapsing, changing shape sometimes even colliding. As galaxies merge, individual stars don't collide, but the original galaxies' energies, gravitational forces and other orbital parameters interact with each other to create a remnant that is not simply the superposition of the colliding galaxies on top of each other, but rather a completely new structure Drakos et al. (2019a). Of interest to this paper is how **major mergers** (where both colliding galaxies are of similar sizes) affect the structure of the remnant's **dark matter halo** which is the non-baryonic matter that extends far beyond the baryon galaxy in a halo. In this paper the **halo shape**, which is the structure of the halo, is defined by the **ellipticity** or the roundness of a remnant's halo. If the halo is a perfect sphere it is **oblate**. If its a squashed ovoid with 2 axis of about the same size its **prolate** and if it has three different sized axis it is **triaxial**.

Understanding how galaxies merge is important because the universe is not static. It is constantly moving and expanding, resulting in galaxies running into each other and merging. Dark matter, in particular, is one of the driving forces of galaxy formation meaning "Dark matter haloes are the exclusive sites of galaxy, group, and cluster formation"Drakos et al. (2019a). As such, studying the effects mergers have on halos can give us valuable insight into not only on what will happen to merging galaxies but also valuable insight into how galaxies are formed in the past. For example, we find that in simulated mergers "MHD halos are rounder than DMO halos at all radii" Prada et al. (2019). It is often seen that older galaxies are smaller and less defined than new galaxies. Being able to analyze these galaxies would help us better understand whether this difference is due to mergers or some other factor of the early universe, like a change in angular momentum.

One thing we know about galaxy mergers is that the ellipticity is greatly dependent on its energy and mass. If we define the factors κ and λ such that:

$$\kappa \equiv \frac{E_0'}{E_0}\left(\frac{M}{M'}\right)^{5/3}, \lambda = \frac{\sqrt{|E_0|}|\mathbf{J}|}{GM^{5/2}}$$

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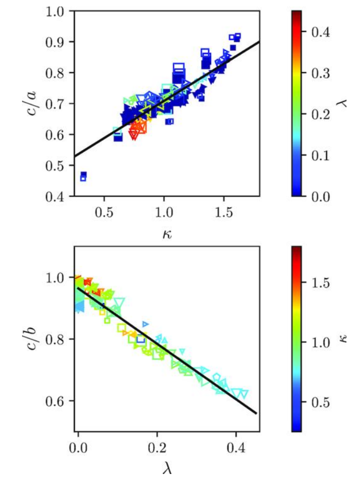

Figure 1. Oblateness of halo bases on κ and λ

We can see a near perfect linear relationship with the ratio between the minor over the major axis (c/a) and minor over the intermediate axis (c/b) respectively, see figure 1 Drakos et al. (2019a). We also know that the density profile of a halo is near universal "regardless of mass or cosmological model" Drakos et al. (2019b). One of the most accurate version of these profiles is the Einasto profile, which is written as:

$$\rho(r) \quad = \quad \rho_{-2} \exp\left(-\frac{2}{\alpha_{\mathrm{E}}}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha_{\mathrm{E}}} - 1\right]\right)$$

in wich α_{E} is the Einasto shape parameter and r_{-2} is the radius where the logarithmic slope is -2 Drakos et al. (2019b). Another thing we know is the usual shape of halos. Studies have shown that halos can be both **triaxial** having three different length axis and prolate (c/b > b/a) with high mass halos being less spherical then the less massive halos, and concentrated halos more spherical still Chua et al. (2019).

One of the biggest questions in the realm of galaxy mergers is how do we simulate accurate mergers and the interplay between dark and baryonic matter. It was only recently we learned that "strong baryonic feedback effects, such as stellar feedback and black hole feedback" are necessary to form disks and late time galaxies Prada et al. (2019). Similarly **N-body simulations**, where the change of a system of N objects is simulated using known equations of model their behavior, are imperfect simulations that do not perfectly model galaxy formation, “because the coupling of baryons and DM can have a significant impact on the structure of DM haloes especially in the inner halo where galaxies reside” Chua et al. (2019). Another question is exactly what effect major mergers have on halo structure Drakos et al. (2019a). While we have a general idea of what the result of a merge will look like and the main factors in said result, the fine details are still little understood.

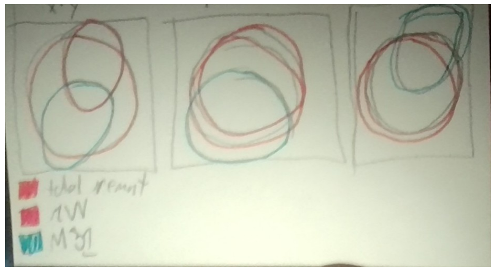

Figure 2. A theorestical sketch of the final figure of the paper. Ellipses are fit to each component of the remant halo as well as the full remnant and ploted over top of each other. This is then repeated for each face of the galaxy, xy, xz, yz

ellipticity	xy	yz	xz
Full Remant	0.13	0.19	0.19
MW	0.12	0.19	0.14
M31	0.16	0.23	0.07

Table 1. Ellipticity of the ellipses from figure 4. First row is the elliptically of the full remnant, second row MW, third row M31. Column has ellipses in the xy plane, second yz plane and third xz plane

2 THE PROJECT

In this paper I will compare the shapes of the MW and M31 components of their remnant's dark matter halo. Using the high resolution simulation data at snap 630 which is at 9 gyr, approximately 2.5 gyr after the initial merger, I will fit ellipses to the density profile of both the total remnant and each individual component galaxy. I will then plot these ellipses and compare the final elliptically and shape to determine how each galaxy contributes to the final shape of the remnant. This fitting and comparing process will be done for multiple angles of the galaxy to get a 3 dimensional understanding of the remnant halo and how it has been affected by the merger.

This study will help us understand the effect major mergers have on halo structures of the remnant. In particular, this study will help advance our understanding of the fate of individual galaxies at the end of a merger and what that means for a remnant. It will also advance our understanding of the accuracy of N body simulations.

My project will study how the original galaxies contribute to the final remnant's halo, allowing us to better understand how individual galaxies effect merges and the resulting halo structure. Similarly my results can be compared to actual remnants and their structure to better understand where and why the simulation differs from reality. This in turn will allow us to better understand the physics behind galaxy mergers and how to better model that with N body simulations.

3 METHODOLOGY.

This paper will use the simulation of the MW-M31-M33 merger generated by Roeland van der Marel and his team. Using the observed M31 transverse velocity from Hubble Space telescope NASA Hubble Mission Team (2025). NOTE:Add rest of simulation data from "The M31 Velocity Vector.III. Future Milky Way-M31-M33 Orbital Evolution, Merging, and Fate of the Sun" https://assets.science.nasa.gov/content/dam/science/missions/hubble/releases/2012/05/STScI-01EVSRDK9HAKSRTDFGD1YE7QJ4.pdf

To determine the contribution of the MW vs. M31 halo particles to the final shape of the remnant. I will start by concatenating the snap 630 MW and M31 files and isolating for only the halo particles. This snap is at time 9 gyr which is long enough after the merger the remnant should have settled. I will use the high-resolution files to avoid the 'noticeable differences' in shape of the galaxy at low kpc from the center that some low resolution simulations experiences Prada et al. (2019). I will then find the center of mass of each object using the CenterOfMass code previous developed and reorientate the remnant so its angular momentum is aligned with z axis. I will then fit an ellipse to the density profile at at semi-major axis of 1000 kpc. This value was chosen as the density contour shows this radius includes about 90% of the total galaxies dark matter which is enough matter to see the larger structure of the remnant without including particles that have been flung too far from the COM. Ellipses will be fit to this radius using photutils to analysis the density profile. I will then graph the fitted ellipses from various perspectives to visually see the shape and distribution of the particles as well as compare the length of axis to evaluate the final shape (figure 2).

My final step will be to graph the fitted ellipse of the system. For each perspective xy, xz, and yz, I will plot the fitted ellipses with respect to each components center of mass. This will allow us to visually see where each component is and its shape. If the ellipses overlap, both galaxies contribute equally to the shape of the remnant but if there is a gap there is not an even distribution of mass.

As this is a Major Merger I expect for galaxies to mix nearly completely, resulting in a “near-complete mixing of old and new material” Frenk & White (2012). Ergo I predict the remnant will be a triaxial ellipsoid with no significant structures. The core will likely be denser than the outer radii but there should not be any significant structures like arms or spirals.

4 RESULTS

Figure 3 plots the density profile of MW, M31 and combined remnant. The first column is the total remnant, the second column MW and the third column is M31. The first row shows the profiles in the xy plane, the second in the yz and the third in the xz plane. All particles tend to gather at the center of the remnant regardless of type. But at farther radii the MW and M31 particles in the xy and xz planes tend to be on opiste sides of each other.

Figure 4 shows ellipses fitted to the density plotted in figure 3to the at a distance of 500 kpc. In all planes one can see some degree of separation between the particles. With the largest being in plane xy and smallest being in plane xz. MW and M31 always lie on opitise sides on the full reamnant. The shape of each ellipse is roughly the same with most being around the average ellipticity of 0.16, see table 1 for full deatils of the ellipticity.

5 DISCUSSION

Figure 4 shows that the particles from MW and M31 are not perfectly distributed among the remnant. Knowing the center of the ellipses, I found that the center of MW and M31 where separated by 294

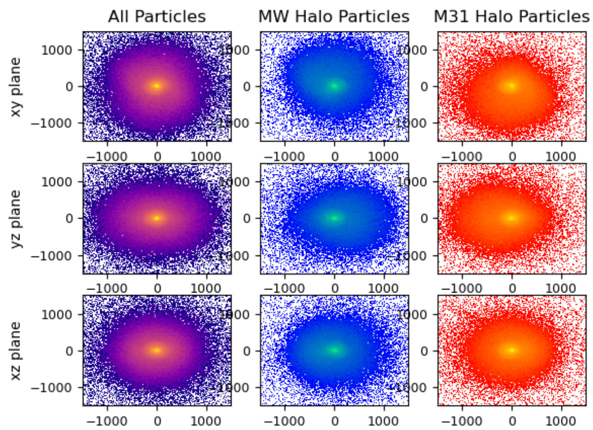

Figure 3. Density profile of MW, M31 and combined remnant. The first column is the total remnant in purple, the second column MW in blue and the third colomn is M31 in red. The first row shows the profiles in the xy plane, the second in the yz and the third in the xz plane.

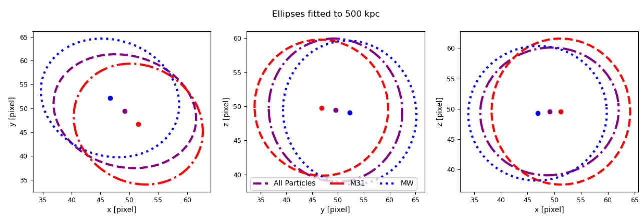

Figure 4. Fitted ellipses to 500 kpc to both the full remnant and its individual components. Full remnant is purple dash-dotted line, MW in blue dotted line, and M31 is red dashed line. The center of each ellipse is plotted as a point in each components respective color. The first section is in the xy plane, second in the yz plane, and last in the xz plane

kpc, separated 222 kpc in the yz plane and 131 kpc in the xz. This means that Mw and M31 are not evenly distributed in the remnant. Rather each galaxy tends to stick to its side of the remnant. This uneven distributed of the MW and M31 does not match the original hypothesis.

This study gives us a better understanding of how halos are shaped by mergers. It agrees with "a near-complete mixing of old and new material" but only to a limted extentFrenk & White (2012). MW and M31 did largely merge, especially towards the core, but did not completely form a homogeneous distribution. This knowledge helps us understand what happens to galaxies when they merge. It will also allow us to better analyze observable remnants. Knowing that particles from individual galaxies tend to stick near each other could help us identify which part of a remnant comes from which galaxy and in turn lead to a better understating of the original galaxies and their effects on the final remnant.

One uncertainty in these findings is if these results stay the same at different radii. It is known that a galaxy can have a different shape at different radii Chua et al. (2019). We can also visually see in figure 3 that both MW and M31 cluster at the center of the remnant clustering to their sides of the object. This likely means that if a smaller radii for the ellipses was chosen, there would be a smaller separation. Another uncertainly is if 2.5 gyr after the initial merger was enough time for the remnant to reach its rest state. If a latter snap shot was chosen, the remnant might have mixed farther, lessening the separation. The simulation its self might also be flawed, as out current understanding the physics governing galaxy mergers is limited so our ability to model mergers is lacking.

The components do have a similar shape to the final remnant. Most of the ellipses have an ellipticity around the averge 0.16, but M31 in the yz plane has an ellipsticy of 0.23 and M31 in the xz plane has an ellipticity 0.07. Both are outliers but are sufficiently close we can conclude that MW and M31 do not have any significant effect on the shape of the final galaxy. The expected shape of the remanent being an ellipse with no significant structures was seen in figure 3.

These results agree with previous studies that the ellipticity of a galaxy is not dependent on the initial galaxies Drakos et al. (2019a). This gives a better understanding of how the initial conditions affect the end result of a merger. Specifically, it confirms that galaxy mergers result in elliptical galaxies and not the complex spiral structure of our own galaxy. Knowing that the shape of a remnant is not effected by the initial galaxies and is instead governed by other properties will give us better insight into galaxy mergers as a whole.

Similarly to the uncertainty on the distribution , a large radii might have resulted in a more significancy change in shape. From figure 3 we can see the distribution of MW and M31 become less circular at larger radii. Taking a larger radii could have drastically effected the elliptically of each component. This could also be effected by the time as which we took out snap shot. With a latter time being more evenly dispersed and shape changing as a result. Like with the analysis of the position on MW and M31, our inability to fully model galaxy mergers with N body simulations might also lead to inaccurate results.

DATA AVAILABILITY

To be added

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