Affects of Component Galaxies on M31-MW Remnant's Final Dark matter Halo Structure

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ABSTRACT

This paper will explore how the original galaxies involved in a major merger affect the final shape and density distribution of the remnant's Halo. This topic is important to understand the effects mergers have on galaxies, specifically the effects on the dark-matter Halo. I will be using the MW-M31-M33 merger generated by Roeland van der Marel and his team to perform this analysis NASA Hubble Mission Team (2025). I analyze where the MW and M31 Halo particles ended up in remnant's halo and how this affects the density distribution and shape of the halo. It was found that the particles tended to be on opposite sides of the galaxy from each other, with the center of the galaxy between the two. I also found that there was no significant change in shape between the MW, M31 and full remnant particles. This confirms that major mergers result in rounder less elliptical halos, but contradicts the commonly held belief that the original galaxies are evenly distributed throughout the remnant.

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

1 INTRODUCTION

Our universe is composed of stars, some of which are bound together into **galaxies** and act in ways Newton's laws and baryons (gas, dust and stars) cannot describe Willman & Strader (2012). 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. We are specifically looking at the structure of the **dark matter halo** which is the non-baryonic matter that is decoupled from the expansion of the universe 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 as defined b. If the halo is a perfect sphere it is **oblate**. If it's 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 halos 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 what will happen to merging galaxies but also 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:

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

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 versions of these profiles is the Einasto profile, which is written as:

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

in which $\alpha_{\rm E}$ 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

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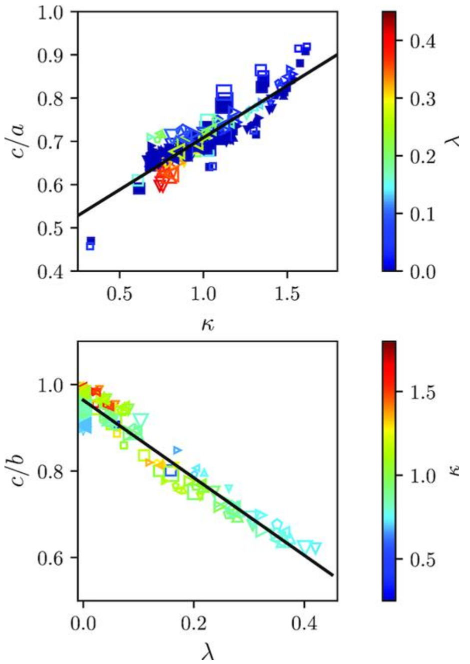

Figure 1. Ratio of the Remnant axis. Minor over the major axis, c/a, on top vertical axis, $\kappa = \frac{E_0'}{E_0}\left(\frac{M}{M'}\right)^{5/3}$ on the horizontal. Minor over the intermediate axis, c/b, as a function of $\lambda = \frac{\sqrt{|E_0|}|\mathbf{J}|}{GM^{5/2}}$ in the bottom figure. There is a color bar showing the value of κ and λ for the simulations the data was taken from beside their respective figures. There is a clear liner relationship between κ and λ with c/a increasing as κ increases and c/b decreasing as λ increases. Drakos et al. (2019a)

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 halos 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.

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 ellipticity 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 NASA Hubble Mission Team (2025). They generated the simulation using the observed M31 transverse velocity from Hubble Space telescope NASA Hubble Mission Team (2025). The profile of the Dark matter halo is modeled by the Navarro–Frenk–White with a c_{vir} = 10 ± 2van der Marel et al. (2012a). The disk has an exponential profile with a scale length R_d and bulge of R_d= 0.5R_{disk} van der Marel et al. (2012b). MW is composed of 500,000 number of dark matter particles, 750,000 disk and 100,000 bulge van der Marel et al. (2012b). M31 is composed of 500,000 number of dark matter particles, 1,200,000 disk and 190,000 bulge. M33 is composed of 50,000 number of dark matter particles, 93,000 disk and no bulge van der Marel et al. (2012b). The scale radius of the dark matter halo is 3[f], 5[f],1.3[g] kpc for the MW, M31 and M33 respectively. The scale radius of the dark matter halo is 0.6, 1.0 kpc for the MW and M31 respectivelyvan der Marel et al. (2012b). M31 is set at a inclination on 77.5 deg and approaches from the SW side of the milkyway van der Marel et al. (2012b). M33 is set at a inclination on 52.9 deg and approaches from the W van der Marel et al. (2012b).

To determine the contribution of the MW and 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 developed in class and reorient 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 500 kpc. This value was chosen as the density contour shows this radius includes about 75% 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 analyze 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. Similarly if the ellipses have significantly different ellipticity they contribute signifgantly to the final shape of the halo.

As this is a major merger, I expect for the galaxies to mix nearly completely, resulting in a "near-complete mixing of old and new material" Frenk & White (2012). I predict the remnant's halo will be a triaxial ellipsoid with no significant structures. The core will be denser than the outer radii but the halo particles should not clump

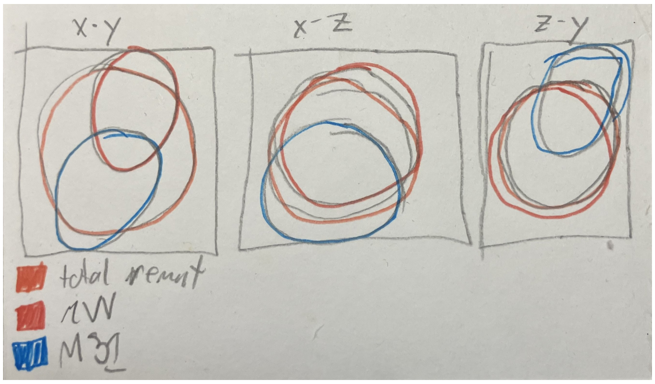

Figure 2. A theoretical sketch of the final figure of the paper. Ellipses are fit to each component of the remnant halo as well as the full remnant and plotted over top of each other. This is then repeated for each plane of the galaxy, xy, xz, yz. The degree of mixing and its effect on the final shape can be measured using the separation of the fitted ellipses and how similar in ellipticity they are.

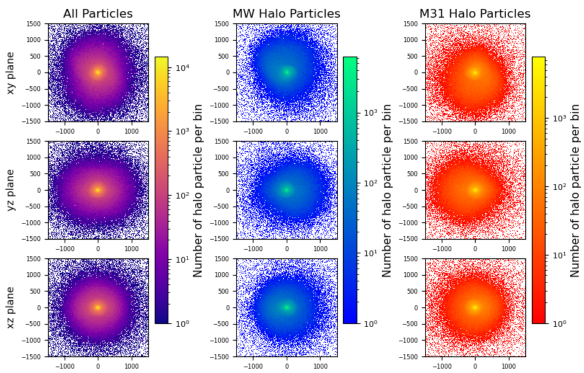

Figure 3. Density profile of MW, M31 and combined remnant. The first column is the total remnant in purple, the second column MW in blue and the third column is M31 in red. Beside each column in respective key for the density of the number of disk pa. The first row shows the profiles in the xy plane, the second in the yz and the third in the xz plane. We can see in that MW and M31 tend to gather on opposite sides of the remnant from each other.

together in any way. The halo while triaxial, should still be relatively round with little to no significant change in the axis of the halo.

4 RESULTS

Figure 3 plots the density profile of MW, M31 and combined remnant at snapshot 630. 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 are densest 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 gather on opposite sides of each other.

Figure 4 shows ellipses with a semi-major axis of 500 kpc fitted to the density plotted in Figure 3. In all planes one can see some degree of separation between the particles. The center of MW and M31 are separated by 294 kpc in xy the plane, 222 kpc in yz and 177 kpc in xz. MW and M31 always lie on opposite sides of the remnant. The shape of each ellipse is roughly the same. Most of the ellipses are around the average ellipticity of 0.16, with seven out of the nine ellipses being within one standard deviation. The full remnant has the same ellipticity in both the yz and xz planes.

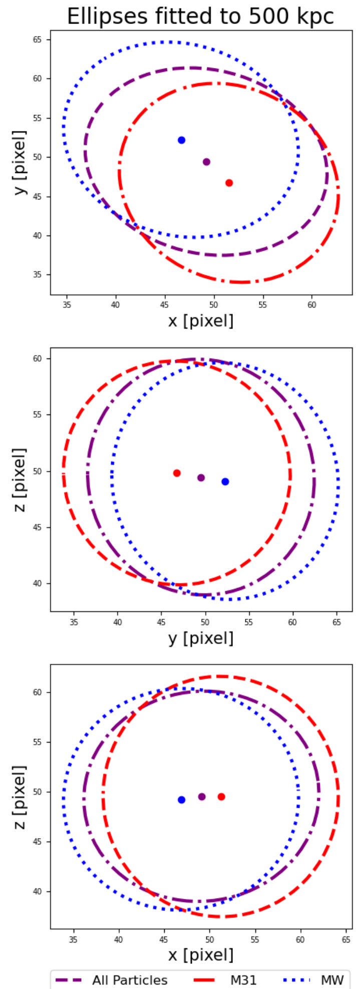

Figure 4. Fitted ellipses to 500 kpc to both the full remnant and its individual components. Full remnant is purple dash-dotted line, MW in blue dotted line, and M31 is red dashed line. The center of each ellipse is plotted as a point in each components respective color. The first section is in the xy plane, second in the yz plane, and last in the xz plane. On the bottom of the plot is a legend with which line links to which galaxy. There is a clear separation between the center of the ellipse proving the halos have not mixed. The ellipses have a similar ellipticity showing that the individual galaxies do not have a significant effect on the final structure of the halo. The center of MW and M31 are separated by 294 kpc in xy the plane, 222 kpc in yz and 177 kpc in xz. The ellipses have an average ellipticity of 0.16 and most of the ellipses are within one standard deviation. The exception being M31 in the yz and xz plane which have an ellipticity of 0.23 and 0.07 specifically

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

5 DISCUSSION

Figure 4 shows that in snapshot 630, 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 were separated by 294 kpc in the xy plane, separated 222 kpc in the yz plane and 131 kpc in the xz. These separations are significant considering that the ellipses all have a semi major axis of only 500 kpc. 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 distribution 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 limited extent Frenk & 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 could lead to a better understanding 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 as well as around 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 later snap shot was chosen, the remnant might have mixed farther, lessening the separation. The simulation itself might also be flawed, as our current understanding of 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 within one standard deviation, the exceptions being M31 in the yz plane with an ellipticity of 0.23 and M31 in the xz plane with an ellipticity 0.07. Both are outliers but are sufficiently close that we can conclude that MW and M31 do not have any significant effect on the shape of the final galaxy. This result agrees with the expected shape of a rounded ellipsoid with no significant structures.

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 rounder dark matter halos then are found in earlier, unmerged galaxies like our own galaxy. Knowing that the shape of a remnant is not affected by the initial galaxies and is instead governed by other properties, will give us a better insight into galaxy mergers as a whole.

Similarly to the uncertainty of the distribution, a large radii might have resulted in a more significant 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 affected the ellipticity of each component. This could also be affected by the time at which we took our snapshot. With a later time resulting in a more even distribution and the 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.

6 CONCLUSION

Throughout this paper I have investigated the dark-matter halo of a remnant and how its shape and density is defined by the galaxies it is made of. This topic is important to understand the effect mergers have on galaxies, specifically the effects on the dark-matter Halo. This paper used the N-body simulation of the MW-M31-M33 merger generated by Roeland van der Marel and his team to help with that task NASA Hubble Mission Team (2025). Their simulation uses a Navarro–Frenk–White density profile with a $c_{vir} = 10 \pm 2$ for the halo van der Marel et al. (2012a). They used 500,000 particles each for the MW and M31 systemsvan der Marel et al. (2012b). For snapshot 630, I analyzed where the MW and M31 Halo particles ended up in the remnant at and how this affects the density distribution and shape of the remnant.

This paper found that the distribution of the particles was not even. When ellipses with semi major axis 500 kpc where fitted to the density profile of the remnant there is a significant difference in the center of the ellipses with respect to the MW and M31 particles. This finding disagrees with my hypothesis, as I was expecting a more thorough mixing of MW and M31. This is significant for the field as it contradicts the belief that major mergers results in a more cohesive mixing Frenk & White (2012).

It was also found that the shape of the full remnant and its component galaxies are very similar. The ellipticity of figures is very similar with only two out of the ellipses outside one standard deviation. The shape is consistent with the elliptical halo predicted in the hypothesis. It also confirms what the science predicted, major mergers result in a rounder less oblong halo that lack the more elliptical shape found in our own galaxy.

This code is limited, analyzing only one time and one radius to fit the ellipses. As such future projects would look at how the shape and position of the particles change at different radii. Using different times could also provide insight into how the distribution of the remnant changes over time and if more time would result in a more thorough mixing of the galaxies. Further analysis of the MW and M31 systems to better model the dark-matter halo and not the approximation that is the Navarro–Frenk–White density profile van der Marel et al. (2012a).

7 ACKNOWLEDGMENTS

I would like to acknowledge the Software used in this paper.

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We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous 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 relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

8 DATA AVALIBILITY

These simulations were made available to me by Dr.Besla as part of my education in ASTR 400B at university of Arizona

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