Structure of the Dark Matter Halo Remnant After the MW–M31 Merger

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ABSTRACT

We investigate the final density structure of the dark matter halo remnant resulting from the predicted major merger between the Milky Way (MW) and Andromeda (M31). Using an N-body simulation snapshot, we assess the density profile of the remnant and compare it to Hernquist and NFW models, focusing on structural relaxation and equilibrium. This project seeks to understand how galaxy mergers reshape dark matter halos and test whether classical density models describe post merger systems.

Key words: Dark Matter Halo – Major Merger – Hernquist Profile – NFW Profile – Virial Equilibrium – Galaxies

1 INTRODUCTION

A primary goal for cosmology and galactic dynamics is to understand the structure and evolution of dark matter halos. The galactic disk and its bright components are only a small part of the total mass of a galaxy, most of which is, in fact, devoid of light but still involves gravity, and is thereby classified as a **dark matter halo**, the huge **gravitationally bound** halo that extends far beyond the **spiral galaxy** structure. This is the indirect evidence for dark matter due to the fact that they affect the formation, interactions and **major mergers** of galaxies. My research focuses on the major merger, the structural result of one of the most dramatic gravitational phenomena.

A major merger occurs when two galaxies of comparable mass collide and are left as one remnant system. These events significantly shape the structure and kinematics of the newly formed galaxy since they disturb stellar orbits and mix dark matter. Through this project, I investigate the remnant halo of the future predicted merger of the Milky Way (MW) and Andromeda (M31). My aim is to determine whether the profile of the post merger dark matter halo conforms to established

theoretical profiles such as the **Hernquist profile** or the **NFW profile**.

Both models show how density decreases with distance from the center of a system. The Hernquist profile describes a spherically symmetric system with a central cusp, and steeper fall off at large radii. The NFW profile is based on cosmological simulations and describes dark matter halos in **Cold Dark Matter Theory** (Frenk & White, 2012). My analysis uses a simulated snapshot of the MW-M31 merger to explore whether the resulting halo follows either of these profiles.

These questions stem from the assumption that, by whatever means they form, dark matter halos will eventually settle down into a quasi-equilibrium state. If this is true, the remnants of a big merger should look like halos that formed in isolation. Under the cold dark matter paradigm, such a model would enhance the universality of halo formation models.

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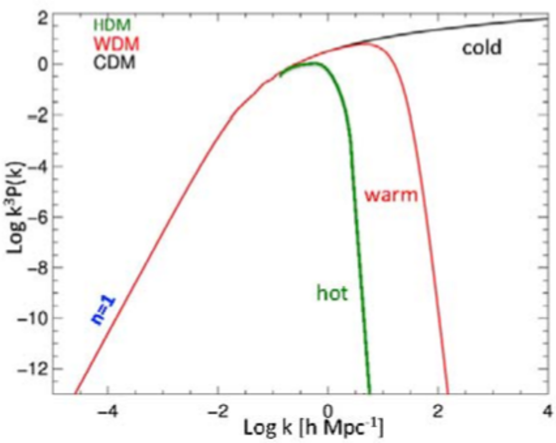

Figure 1. Power spectrum for cold (CDM), warm (WDM), and hot (HDM) dark matter. CDM supports concentrated halos on small scales, motivating the expectation for a cusp-like density profile (Frenk & White, 2012).

These questions also help with relaxation timescales and the inner versus outer halo structure. However, dynamical models are more of an average description of the overall structure of the halo, and simulations give high precision data to test these models throughout all scales; from the very central regions to the halo outskirts. Previous simulations suggest that mergers may lead to mass redistribution, a flattened cusp, and relaxation through violent mixing (Abadi et al., 2010; Prada, 2019). Some studies suggest the inner slope may be altered or that deviations may arise compared to classical profiles (Drakos & Yamaoka, 2019a; Drakos & Mendoza, 2019b). How well theory and simulation reproduce reality in non-idealized systems is defined by the fitting process and the limitations.

2 THIS PROJECT

This study aims to answer the following questions:

(i) What is the radial density profile of the dark matter halo that forms after the MW–M31 merger?
(ii) Does this profile match a Hernquist or NFW profile, and what are the best-fit scale parameters?
(iii) Has the remnant reached **virial equilibrium**, and over what range is it dynamically relaxed?

To address these questions, we focus on the dark matter component only from a simulated snapshot of the MW-M31 merger at a time after the galaxies have fully come together into a single remnant system. Using this snapshot (snapshot 801), we extract particle data representing the final structure of the dark matter halo.

We aim to determine the spherically averaged radial density profile of this remnant by binning the particles into logarithmic radial shells, computing densities, and fitting both Hernquist and NFW functional forms. The fitting process will return scale parameters (a and r_s) that describe the characteristic structure of the halo.

In addition to structural fitting, we evaluate the average radial velocities in each shell to assess dynamical relaxation. The presence of high radial velocity dispersions would indicate the system is still settling, while values near zero would suggest equilibrium. We specifically use a cut of $|\langle v_{\rm rad} \rangle| < 30$ km/s to define relaxed regions.

This project's strength lies in applying classical analytic models to a complex post-merger system to test their continued applicability. We are not only fitting known profiles but also exploring the limitations of the models in describing dynamically evolving systems. The goal is to evaluate how far out in radius the system can be described by these profiles and whether the central cusp shows signs of disruption or smoothing due to the merging process.

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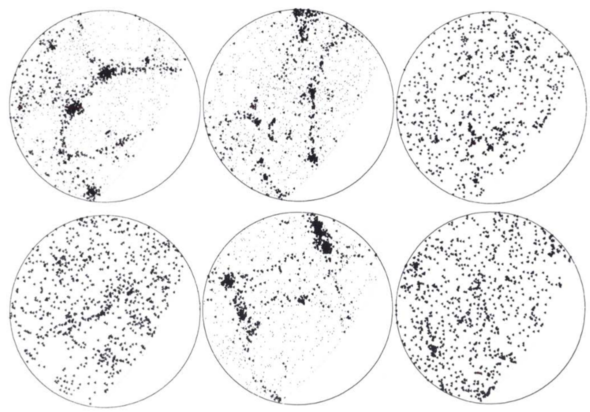

Figure 2. Dark matter halo evolution over time, showing how major mergers and relaxation processes affect the density structure of the remnant halo. Each panel represents a different merger stage, illustrating the redistribution of mass and the formation of the final density profile. This visualization provides insight into the transformation of the dark matter distribution during the MW–M31 merger. Adapted from Navarro et al. (1997).

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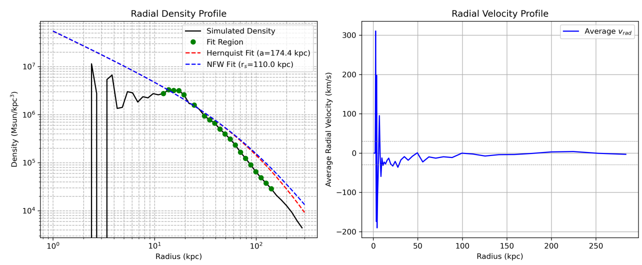

Figure 3. Left: Density profile with Hernquist (red) and NFW (blue) fits. Green points show relaxed bins used in the fit. Right: Radial velocity profile shows near-zero average beyond 10 kpc.

3 METHODOLOGY

For this I used dark matter particle data of a simulation, tracking the merger between Milky Way and Andromeda. The data is provided in two text files, MW_801.txt and M31_801.txt, as well as containing position, velocity, mass, and particle type information. I will only use **particle type 1**, which represents dark matter particles.

I also wrote a Python program that reads both files using a custom ReadFile function from homework 2, which filters the dark matter particles out, and merges them into a unified data structure. In order to analyze the halo as a single system, we compute a mass weighted center of mass (COM) by averaging the positions of all of the dark matter particles. Then I recenter all coordinates on the COM for that to eliminate any global offsets between the galaxies.

I calculate the radial distance of each particle from the COM, and its radial velocity. Radial velocity is the velocity vector projecting along the direction from center to particle. This is key to determining whether particles are inflowing, outflowing or stably orbiting. A large average radial velocity could imply that the system is still settling, while a small average suggests that it has dynamically relaxed.

The halo is binned in 50 logarithmic radial shells ranging from 1 to 300 kpc. For each shell, I derive total mass and mean radial velocity. Mass in each shell is divided by volume to calculate the density. I have included some preliminary analysis to isolate the relaxed regions by filtering out the bins at $|\langle v_{\rm rad} \rangle| > 30$ km/s and setting the fit region to be between 10 and 150 kpc.

The filtered data was fitted with both Hernquist and NFW models using SciPy's curve_fit(). Various forms of the density profile $\rho(r)$ exist, such as the NFW profile:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

or the Hernquist profile:

$$\rho(r) = \frac{\rho_0}{(r/a)(1 + r/a)^3}$$

with r_s and a the characteristic scale parameters. These are fitted to the density values of the selected bins to give the best scale lengths. Residuals from the fitting process are also output, which can be used to judge how good the fit is.

Hypothesis: I hypothesize that the remnant halo will closely follow an NFW or Hernquist profile in its outer regions, particularly beyond 10 kpc, due to virial relaxation. However, deviations may persist within the central 10 kpc, where dynamical mixing has not fully equilibrated.

Following the procedures outlined above, we now present the resulting density profile, velocity profile, and spatial structure analysis of the dark matter halo remnant formed by the MW–M31 merger.

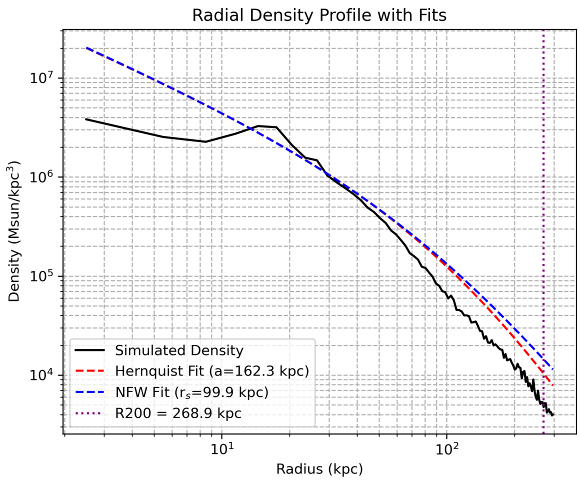

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Figure 4. Radial density profile of the MW–M31 merger remnant. The black curve shows the simulated density; the red dashed line is the Hernquist fit; and the blue dashed line is the NFW fit. Only bins satisfying $|\langle v_{\rm rad}\rangle| < 30$ km/s and $r > 10$ kpc were used for fitting. The vertical dotted line marks R_{200}. The Hernquist profile provides a slightly better fit based on MSE, indicating a relaxed halo structure.

4 RESULTS

In this section, we present three figures generated from the analysis of the MW–M31 merger remnant.

4.1 Figure 4: Radial Density Profile with Hernquist and NFW Fits

Figure 4 tracks how the dark matter is spread out from the center of the remnant, averaged in every direction. The solid black line shows what our simulation actually found. For comparison, the red and blue dashed lines show two popular models: The Hernquist and NFW models, that we fitted to the data.

To keep things accurate, we only included particles that are moving pretty slowly (less than 30 km/s in the radial direction) and are at least 10 kiloparsecs away from the center. This way, we're focusing on the more settled, stable regions. There is also a vertical dotted line marking the virial radius (labeled R_{200}), which is the boundary we get from looking at how much mass is enclosed.

The main takeaway is that both the Hernquist and NFW models do a pretty good job matching the outer parts of the merger remnant. But when we look closer using a Mean Squared Error (MSE) analysis, the Hernquist profile actually fits a bit better. This tells us that the remnant's mass is distributed in a way that's typical for classic, well settled systems.

The Hernquist model is known for describing things like elliptical galaxies and the leftovers from big mergers, it has a sharp increase in density near the center and a steep drop off farther out. The fact that this model fits best suggests that after the Milky Way and Andromeda merged, their combined halo ended up with a steeply declining outer density, rather than the more gradual decline you would expect from the NFW model, which usually forms when galaxies grow slowly over time.

This means that the chaotic mixing during the merger (also called violent relaxation) did a thorough job of blending the dark matter, making the outer regions of the remnant steeper, similar to structures observed in the early universe. As a result, the outer regions of the remnant look more like those of an elliptical galaxy than a typical "primordial" halo that formed slowly.

4.2 Figure 5: Radial Velocity Profile

Figure 5 presents the average radial velocity $\langle v_{\rm rad}\rangle$ as a function of radius. The horizontal dashed lines at ± 30 km/s indicate the threshold for defining relaxed regions. Beyond approximately 10 kpc, the average radial velocity remains close to zero, implying that the outer halo has achieved dynamical equilibrium.

The main result here is that the system appears dynamically relaxed beyond 10 kpc, justifying the selection of the radial fitting region for the density profile models.

4.3 Figure 6: 2D Contour Map of Dark Matter Particle Distribution

Figure 6 is a 2D density map of dark matter in the merger remnant, centered on its core. The colors show how densely packed the dark matter particles are across the field (on a log scale).

While radial profiles give us a "by the numbers" view, this contour plot lets us visualize the remnant's overall shape. The symmetry and tight concentration toward the center suggest the system has settled into a calm state, meaning there is no obvious signs of chaos, leftover mess from the collision, or weird distortions.

5 DISCUSSION

The radial density profile analysis demonstrates that the remnant halo closely follows a Hernquist profile beyond 10 kpc, with a lower Mean Squared Error compared to the NFW fit. This result supports the hypothesis that the outer regions of the remnant would relax into a classical halo structure post merger. The preference for a Hernquist like fit aligns with

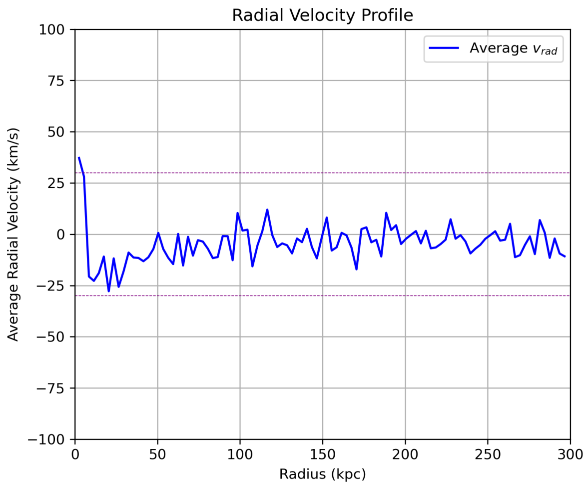

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Figure 5. This plot tracks how fast material is moving toward or away from the center of the Milky Way–Andromeda (MW–M31) merger remnant, on average. The horizontal dashed lines at ±30 km/s km/s show our cutoff for what we consider "relaxed" regions. Once you get past 10 kiloparsecs from the center, the radial velocity stays close to zero-which basically means the outer halo has settled into a stable configuration. This near zero motion beyond 10 kpc supports the idea that the outer parts of the merger remnant have calmed down after the galactic collision, unlike the more chaotic inner regions.

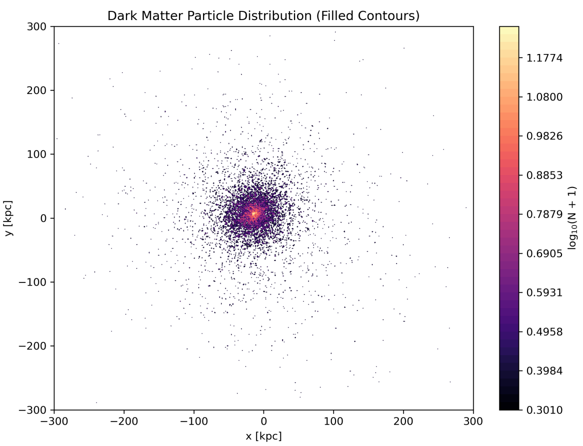

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Figure 6. 2D filled contour plot of the dark matter particle distribution for the MW–M31 merger remnant, projected onto the x–y plane. Color indicates $\log_{10}$(N + 1) particle density. The nearly symmetric structure suggests that the halo is largely dynamically relaxed, supporting the conclusions drawn from radial velocity and density profile analysis.

prior work suggesting that major mergers can result in elliptical structures (Abadi et al. 2010).

The radial velocity profile provides further evidence that the system has achieved dynamical equilibrium. The radial velocities remain near zero, satisfying the relaxation criteria used in this analysis. This observation is consistent with the results of Drakos & Yamaoka (2019a), who found that merger remnants quickly virialize and resemble isolated halos.

The 2D contour map of the dark matter distribution also support these conclusions. The remnant shows a high degree of symmetry and central concentration, with no strong evidence for unrelaxed features. This supports the interpretation that the system has fully relaxed and the classical density profiles remain valid descriptors of post merger halo structure.

Uncertainties in the analysis mainly arise in the central regions ($r < 10$ kpc), where dynamical mixing may not be complete. Moreover, assumptions of perfect spherical symmetry may not fully capture any minor triaxiality or substructure in the remnant. Additionally, the cut at $|\langle v_{\rm rad}\rangle| < 30$ km/s introduces sensitivity to the exact threshold chosen for defining relaxation.

Overall, these results provide strong support for the idea that classical models like the Hernquist profile remain applicable even for major merger remnants, reinforcing the universality of dark matter halo structure formation under the Cold Dark Matter paradigm.

6 REFERENCES

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