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.

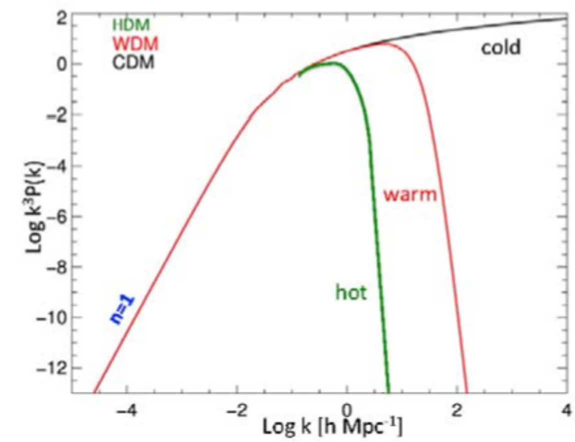

Figure 1. Power spectrum for cold (CDM), warm (WDM), and hot (HDM) dark matter. CDM supports concentrated halos on small scales, motivating the expectation for a cusp-like density profile (Frenk & White, 2012).

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 pro- files (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-only component from a simulated snapshot of the MW-M31 merger at a time after the galaxies have fully coalesced 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 such models in describing dynamically evolving systems. Our 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.

3 METHODOLOGY

For this I used dark matter particle data from snapshot 801 of a simulation tracking the merger between Milky Way and Andromeda. This image depicts the one system of merged galaxies. 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.

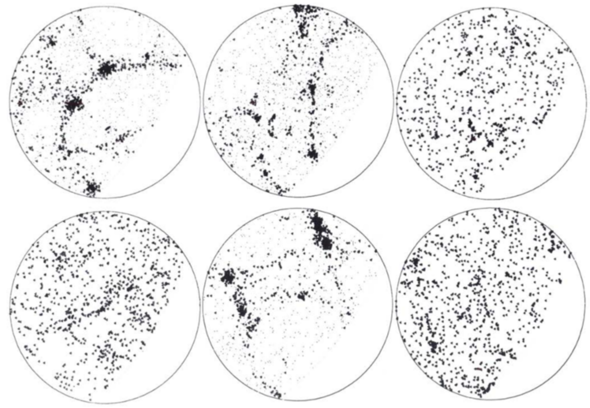

Figure 2. Dark matter halo evolution over time, showing how major mergers and relaxation processes affect the density structure of the remnant halo. Each panel represents a different merger stage, illustrating the redistribution of mass and the formation of the final density profile. This visualization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

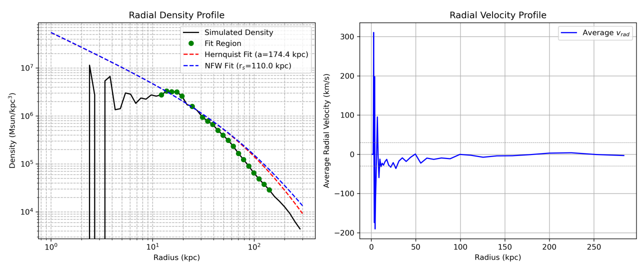

Figure 3. Left: Density profile with Hernquist (red) and NFW (blue) fits. Green points show relaxed bins used in the fit. Right: Radial velocity profile shows near-zero average beyond 10 kpc.

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 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.

4 REFERENCES

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Reference from Homework 4

Reference from Homework 6

Reference from Lab 4