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ASTR 400B: The Final Density Profile of the Dark Matter Halo of the Milky Way and Andromeda Galaxy Merger*

Rianne Kooi,[1]
(Dr. Gurtina Besla)

[1] *University of Arizona Department of Physics*
1118 E. 4th Street
Tucson, AZ 85721, USA

ABSTRACT

N-body simulations can tell us a great deal about what the fate of our universe has in store for us even billions of years down the line. In this paper, we are particularly interested in what the N-body simulation of the Milky Way and Andromeda galaxies can tell us about the most unknown aspect of our universe– the dark matter halo. Studying this, almost abstract, idea will allow us to predict the next steps of these two galaxies, and if more galaxies can be made from their dark matter halo. In particular, we are interested in studying the final density profile of the dark matter halo after the merger. The final density profile is crucial to understanding how galaxy formation is created within dark matter halos. We found that as the radius of the merger remnant increases, the density of of the dark matter decreases and that the concentration of the dark matter remnants is smaller than the initial concentration of the dark matter particles in the individual galaxies. This indicates an obvious change of the concentration before and after the merger.

Keywords: Major Merger — Merger Remnants — Galaxy Merger —— Dark Matter Halo — Hernquist Profile

1. INTRODUCTION

1.1. *Defining*

The Milky Way (MW) and Andromeda (M31) galaxies are destined to collide in approximately 4.5 billion years, and being the two most massive galaxies in the Local Group (LG), this brings forward extremely important questions in regard to galaxy evolution. In particular, the final densities of various particles of the merger. The dark matter halo of a galaxy are gravitational bound particles of dark matter, that spherically extends throughout the visible portion of a galaxy and usually beyond that visible portion. After the merger, the remnants that remain can tell us a great deal about the fate of our LG, our galaxy, and even our home planet. In addition to the information that is given to us when we simulate the merger, we can even predict future plans of our galaxy and LG.

1.2. *Importance to Galaxy Evolution*

A galaxy, defined as "a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity," Willman & Strader (2012) can undergo several different phases throughout its time in our universe, including what could happen at the end of its life– a merger. The evolution of a galaxy, or multiple galaxies, and their interactions can tell us a lot about how galaxies form, die, and change over time. In Wechsler & Tinker (2018), the very first sentence states that our current understanding of galaxy formation alludes that every galaxy forms within a dark matter halo. That very fact illustrates just how important the evolution of the dark matter halo of a galaxy, or group of galaxies, is to our understanding of galaxy evolution is. The very beginning of galaxies start with the dark matter halo, so understanding its density, velocities, mass, and other quantities will tell us if more galaxies can form in that environment. Will a new galaxy form from the MW-M31 merger?

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In terms of our own galaxy evolution, the dark matter halo is important to our understanding because dark matter represents a little over 90 percent of the mass in our galaxy. When MW collides with M31, the overwhelming amount of dark matter of the two galaxies will be one of the focal points of how the final product of the merger will look. Understanding the the dark matter halo remnants of the collision is crucial to how our LG will look, even if we can't see the mass that makes up most of our universe. It's also important to understand what the density looks like so that we can predict what will happen following this collision. What mergers will happen next? What will those collisions look like once they are complete? What does this tell us about the formation of MW and M31?

1.3. *Current Understanding*

Currently, there are several research pushes for dark matter halo density profiles following galaxy mergers. In Frenk & White (2012),

The dark matter halo evolution of galaxy mergers research as seen in Drakos et al. (2019a) delves into what happens to the density of the dark matter halo of mergers. The researchers utilized 6 different profiles in creating the simulations described here: the first profile that they used was the Navarro–Frenk–White (NFW) profile, which is defined as:

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

They also utilized the Einasto (Ein) profile, whihch is defined as:

$$\rho(r) = \rho_{-2} exp(\frac{2}{\alpha_E}[(\frac{r}{r_{-2}})^{\alpha_E} - 1])$$

They created four iterations of the NFW profile, and two iterations of the Ein profile. For 2 of the NFW profiles, they utilized an exponential cutoff, which can be seen in Figure 1 labeled as NFWXSlow and NFWXFast. The other two NFW profiles removed unbound particles outside a specified region, which can be seen in Figure 1 label as NFWT10 and NFWT15. Lastly, the two iterations for the Ein profiles utilized different shape parameters, one with an $\alpha_E = 0.15$, denoted as EinLow for the low shape parameter, and one with an $\alpha_E = 0.3$, denoted EinHigh for the high shape parameter. In figure one, they also change whether the initial velocity was tangential, (denoted T) or radial (denoted R).

The plots of the 6 different profiles that I just mentioned illustrate the density as a function of radius. The

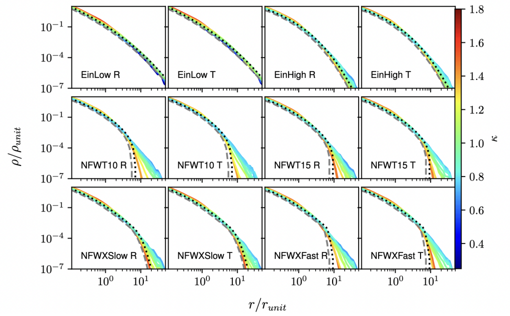

Figure 1. Figure from Drakos et al. (2019a), the density profiles of the halo remnants

profiles have been colored to represent the relative energy parameter κ. As one can see in Figure 1, at large radii, the density is changing in a more prominent way as compared to its small radii counterpart. They also found that the angular momentum of the galaxy has very little effect on the average density.

In Drakos et al. (2019b), the researchers outline how the dark matter halo will behave in terms of the shape, size, and spin. The physical attributes of the dark halo remnants will play a significant role in how the density is concentrated. How halos are structured are very closes related to the merger history, and how these halos are structured will impact the density of the dark matter in the final form after the collision.

1.4. *Current Questions*

Some of the main questions regarding dark matter in mergers comes from Drakos et al. (2019a), where they state that the density of the haloes drops as they grow in size, but the mechanism for this happening is very unclear. The researchers hypothesize that this could be due to the fact that they are only considering a very simple model for major mergers: mergers that have equal-mass, are binary, and non-rotating, among other assumptions.One of the other issues that the researchers found was how their results apply to more realistic mergers. Very simply, their assumptions of equal-mass and isolated binary mergers, are very rare in the acutal universe. Drakos et al. (2019a).

2. THIS PROJECT

2.1. *Introduction*

In this paper, we will be studying the density profile of the dark matter halo of the MW-M31 merger. We will accomplish this by utilizing the N-body simulation data from van der Marel et al. (2012). We will investigate how the dark matter halo density changes as the radius increases across the remnants of the merger. We will attempt to fit an analytical model to the density profile calculated and illustrate this in a plot of density versus radius.

2.2. *Motivating Question*

We are specifically addressing if the final density profile of the dark matter halo fits the Hernquist Density Profile, from Hernquist (1990) can be described as:

$$\rho(r) = \frac{M}{2\pi}\frac{a}{r}\frac{1}{(r+a)^3}$$

Where M is the total mass and a is the scale factor. Previous work explored different density profile models such as the NFW profile and the Einasto profile, but figuring out if the density profile fits the Hernquist profile will allow us to make discoveries about what conditions are required for galaxy formation.

2.3. *Importance of Question*

The importance of fitting the final density profile of the merger can help us understand more about what is needed in order to have new galaxy formation occur. By finding the model that best represents the final density profile of the dark matter halo remnants, we can accurately predict if galaxies will be able to form from the dark matter remnants. As seen in Cintio et al. (2014), we can examine the properties of the concentration of the dark matter remnants to examine the "star forming efficiency."

3. METHODOLOGY

3.1. *Introduction to Simulation*

This project utilized an N-body simulation from van der Marel et al. (2012), which is defined as a simulation of a system of particles that are under the influence of physical forces, like gravity, etc. By utilizing this data, we were able to extract the important information needed to find the final density profile of the merger remnants, like the mass and the radius at which the particles are located. The simulation that was utilized has 800 snapshots of the MW and M31 galaxies that include data on the mass of particles, the distance where the particles are located, and various velocities of the particles. We'll be making use of the 0th snapshot and the 800th snapshot. This will allow us to compare the initial density to the final density.

3.2. *Approach*

To find the final density profile of the merger, in simple terms, we need to find the final mass enclosed of the dark matter halo and divide by the volume. We closely modeled the process utilized to find the mass profile in homework 5, and the results of this can be seen in Figure 2. While we closely modeled the process form homework 5, we needed to fix a few parts of the calculation. The first thing we had to accomplish was combine the two data sets of MW and M31. We accomplished this by first combining the data sets of MW and M31. This was done by using np.append in the MassProfile class as well as the CenterOfMass class to combine the two data sets into one data set that included the masses of both MW and M31. Once this was complete, we were able to find the total mass enclosed within the radii of the dark matter halo. After we found the enclosed mass, we found the density by creating a new function DensityEnclosed that found the spherically averaged density of the dark matter halo. The function found the density enclosed in small chunks of radius and stored it as an array of values.

3.3. *Description of Plots*

Two plots were needed for the initial conditions of the two galaxies. The first plot should be the density profile of MW at the 0th snapshot, with the y-axis being the logarithm of the density in solar masses per unit volume vs the radius of dark matter halo in kpc. The second plot, which should depict the initial density profile of M31, is the same as MW's plot. Where the y-axis is the logarithm of the density in solar masses per unit volume and the x-axis is the radius of the dark matter halo. The third plot that is needed is a plot of the final density profile of the MW-M31 dark matter halo remnant in the similar veiin as the first two plots. Lastly, I need a final plot that illustrates the Hernquist model in comparison to the final density profile found utilizing my DensityEnclosed function. To summarize, the DensityEnclosed function will complete the following calculation in simple terms: ρ = mass enclosed / spherical volume at a radius r[i] - r[i+1] where i is the index that we loop over.

3.4. *Hypothesis*

As seen in Drakos et al. (2019a), we anticipate that the dark matter halo remnants of the MW-M31 merger will become more concentrated than that of when they were separate. I also believe that I will be able to fit the Hernquist model to the density of the dark matter halo. We can anticipate that the shape of the plots will illustrate a high concentration of dark matter particles near the center of the dark matter halo and a lower concentration of dark matter particles near the edge of the dark matter halo, and illustrate a near-parabola like shape.

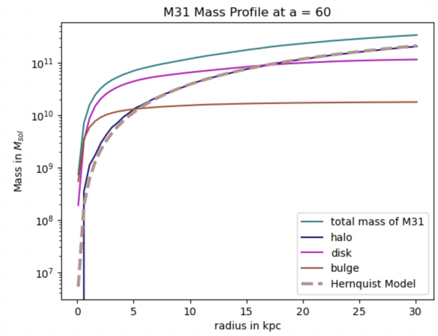

Figure 2. Figure from ASTR 400B: Homework 5 by Rianne Kooi, M31 Mass profile

4. RESULTS

In Figures 3 and 4, we see the initial density profiles of the two galaxies, MW and M31 respectively. They are both most concentrated near inner most radius of the dark matter halo, and trails off as the radius increases. This was done by utilizing the MassProfile Class created, along with the DensityEnclosed function I created for this project. This is the shape of the graph that we are anticipating, where there is a high concentration of dark matter nearest the middle of the halo, and the lowest concentration of dark matter nearest the edge of the halo. A log axis was utilized to illustrate the complexities of the graph, rather than just illustrating a graph that hugs the y-axis extremely closely when there was no logarithm was utilized.

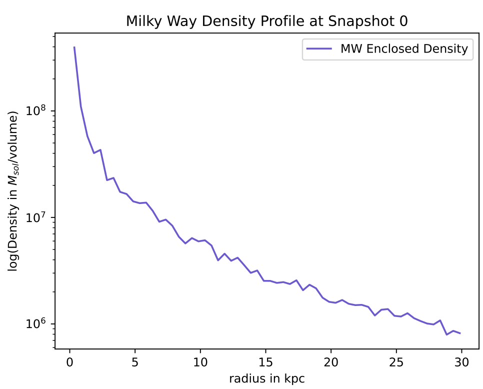

Figure 3. This figure depicts the density profile measured at snapshot 0, the initial density profile of the Milky Way Galaxy. The y-axis is the log of the denstiy, in units of solar masses per volume and the x-axis is the radius, in units of kpc.

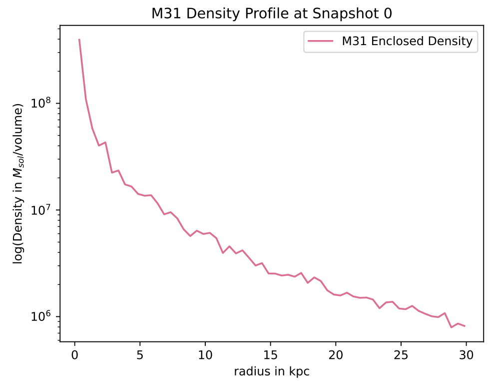

Figure 4. This figure depicts the density profile measured at snapshot 0, the initial density profile of the Andromeda (M31) Galaxy. The y-axis is the density, in units of solar masses per volume and the x-axis is the radius, in units of kpc.

Figure 5 depicts the final density profile of the the MW-M31 merger remnants. The graph also illustrates the shape that was anticipated. The concentration of dark matter is highest when nearest the center of the halo, and lowest when nearest the edge of the halo. Again, a logarithm was used to illustrate the complexity of the graph. Figure 6 depicts the final density profile

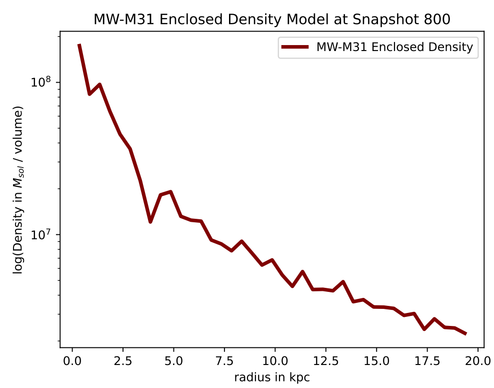

Figure 5. This figure depicts the final density profile of the merger– the combined density at snapshot 800. The y-axis is the density in units of solar masses per volume and the x-axis is the radius in units of kpc.

of teh MW-M31 merger remnants, in addition to the attempted Hernquist model fit on the same plot. It is important to note that it mimics the shape of the plot, but is a few orders of magnitude off from the final density profile. There are a few hypotheses for this, that I will attempt to explain in the next section. Nonetheless, the logarithm of the density was used to illustrate the graph in a more detailed way.

5. DISCUSSION

The first thing I wanted to investigate the difference between the initial density profiles of both of the galax-

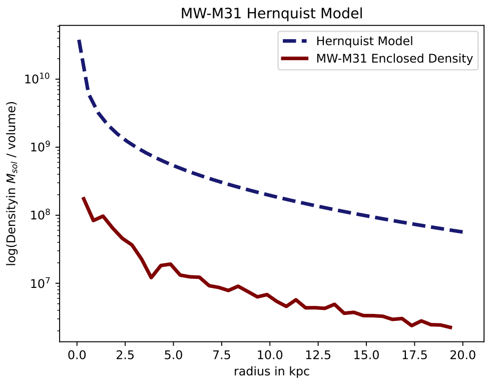

Figure 6. This figure depicts the final density profile of the merger alongside the Hernquist Density Model. THe y-axis is the density in units of solar masses per volume and the x-axis is the radius in units of kpc.

ies to the final density profile of the MW-M31 merger. Both galaxies initially, as seen in Figures 3 and 4, illustrate a higher concentration of dark matter particles near the center of the halo in comparison to the halo remnants, as seen in Figure 5. This is almost the exact opposite of what I was anticipating. I was anticipating that the final profile of the remnants would have a higher concentration of dark matter particles due to the simple fact that the merger occurs and combines the two densities of dark matter particles. This does mimic the work seen in Drakos et al. (2019a), in terms of the shape of the density profile. This is important to our understanding of galaxy evolution because if there is a lower concentration of dark matter particles, and galaxies are formed in the dark matter halo, there is expected to have a lower probability of future galaxy formation in the "new" dark matter halo from the remnants of the merger.

The second thing I wanted to investigate was how well the Hernquist Density Model would fit to the final density profile of the merger remnants. However, as seen in Figure 6, the model did not fit exactly as anticipated, and is off my a few orders of magnitude. This could be because of a number of things, but I anticipate that there was a human-error in terms of my coding abilities. The Hernquist Model does mimic the shape of the final density profile that was calculated, but lacks the precise values that were initially anticipated. This result is difficult to explain the importance in terms of galaxy evolution since the Hernquist model that was created does not properly represent the final density profile calculated, but this can certainly be explored more in future work.

6. CONCLUSION

Utilizing N-body simulations in astrophysics research can explain several properties of galaxy evolution, which is what we set out to do. In particular, we can find the final state of galaxy mergers, and in this project, we set out to find the final density profile of dark matter halo remnants of the MW-M31 merger. The lack of knowledge of dark matter in our universe made this research especially difficult, but also all the more important for our understanding of galaxy evolution. We explored what the initial density profile would look like of the two galaxies before the merger, as well as the final profile after the merger.

We found that the final density profile of the merger illustrates a lower concentration of dark matter particles in the merger, at snapshot 800 in comparison to the initial density profile of the two galaxies separately, at snapshot 0. This was extremely different than what we initially anticipated, and illustrates that even the most massive galaxies can have unexpected results.

In the future, we'd like to try to fit the density profile to different models such as the NFW model or the Einasto model to get a better, full picture, understanding of what the final density profile is most like. I would also like to explore why exactly the concentration is lower after the remnant. If the N-body simulation that was utilized had more data that extended beyond snapshot 800, I would also like to investigate if a new galaxy would be able to be formed from the dark matter halo that remains after the merger and explore the implications of its new dark matter halo and its evolution, and if it will endure another merger.

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