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The Final Density Profile and Concentration of the Milky Way and M31 Major Merger Remnant

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1. INTRODUCTION

The topic of interest for this research assignment is regarding dark matter haloes, particularly the dark matter halo formed by the Milky Way and Andromeda future major merger event. A major merger is defined to be a massive galactic collision. The research project will explore the final density profile of the corresponding halo merger remnant and how it changed from its initial profile. A halo merger remnant is a the dark matter halo as a result of a merger event. In addition, the concentration parameter of the dark matter halo profiles for the Milky Way and Andromeda will be compared with its initial and final stage of the merging process. Concentration parameter is the ratio between the radius of the edge of the galaxy, R_{200} to the scale radius, R_{scale}. With that, the concentration parameter, c can be expressed as the following,

$$c = \frac{R_{200}}{R_{scale}}$$

It has been widely accepted that dark matter contributes 85% of the matter in the universe Planck Collaboration et al. (2018). Hence we expect dark matter to influence the structure and evolution of galaxies. For example, the scale radius of stellar disks is believed to be proposal to the density of dark matter halos. It has been speculated that such relationships arise because of major mergers(Drakos et al. 2019a). The potential correlation can be validated by studying the major merger of two spiral galaxies through numerical simulations.

Furthermore, by investigating the merger remnant of the Milky Way and Andromeda, we can form a better understanding of the evolution of dark matter haloes. The evolution of the dark matter density profile of the merger remnant will be investigated and and compared against the initial density profiles from Milky Way and Andromeda.

Another importance of understanding galaxy evolution of studying galaxy mergers is that we can verify theories with observations. The profiles in which dark matter is expressed in merger remnants in the simulation can possibly test the hypothetical Cold Dark Matter paradigm. The universal density profiles of dark matter haloes are described by the Navarro-Frenk-White (NFW) form (Drakos et al. 2019a).

$$\rho_{NFW}(r) = \frac{\rho_0 r_s^3}{r(r+r_s)^2}$$

where ρ_0 is the characteristic density and r_s is the scale radius. However, Drakos et al 2019 suggest that Einasto density profiles are better expressed instead with the consideration of the profiles structure(Drakos et al. 2019a).

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

where ρ_{-2} is the density where the logarithmic slope is -2, a_E is the shape parameter, and r_{-2} is the radius where the logarithmic slope is -2. The paper also states that equal massed galaxies such as Milky Way and Andromeda, there will only be a subtle difference in density profiles between initial haloes and haloes of merger remnants (Drakos et al. 2019a). This is can be explained with the nature of self similar evolution of 2 equal mass mergers (Drakos et al. 2019a). In regards to the changes in concentration, the Drakos et al 2019 concluded that high energetic mergers will result to an increase in concentration. Whereas, low energetic mergers causes a decrease from its initial concentration (Drakos et al. 2019a).

An open topic questions regarding halo density profiles is that the edge of the halo is questionable (Diemer et al. 2013). Another open question is that major merger affects the evolution of halo structure (Drakos et al. 2019b). A major merger event consist of many degrees of freedom such as the orbit, mass profile, and shape to determine the complete structure of the final remnant (Drakos et al. 2019b).

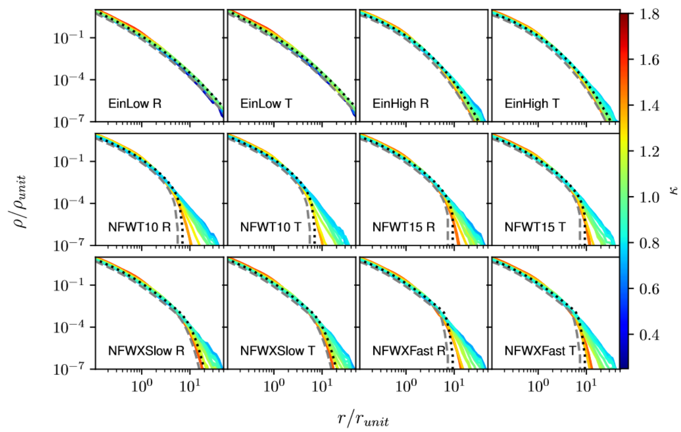

Figure 1: Plots of Einasto and NFW density profiles of halo remnant. The grey dashed lines indicate the initial halo profile, black dotted lines show the initial conditions with rescaled radius, and the colored lines are the merger remnant profiles with different energy change. The suffix of each density listed describes the initial velocity being tangential (T) or rotational (R).

2. THIS PROJECT

The aim for this research project is to find out the final halo density profile of the future Milky Way and Andromeda major merger remnant. The final density of the merger will be compared with 4 density profiles within different snapnumbers through overplots. This will illustrate if the halo merger remnant evolves differently than its initial Hernquist profiles. Moreover, the paper will also investigate the concentration of the Milky Way and Andromeda merger remnant throughout 4 key events: before collision (snapnumber 0), initial collision (snapnumber 350), final collision (snapnumber 455), and after collision (snapnumber 801) of the major merger event.

As mentioned in the Introduction, the specific open question that this research project will address is how major mergers affect the overtime change in halo structure. With multitudes of degrees of freedom embedded in this particular merger event, this paper utilizes simulations instead to restrict degrees of freedom as constraints.

This open question is a significant step on understanding the evolution of galaxies. By formulating a simulation of this major merger, theories in astronomy such as the self similar evolution occurrence between equal mass galaxies will be tested. From here, the conjunction between computational physics and observational astronomy can help formulate connections which results into a better understanding on the subject matter. Generally, this paper will address the open question regarding how mergers evolve overtime by setting a particular initial halo density profile and then using simulation data snapshots to analyze the change in density profiles throughout key stages of the major merger event.

3. METHODOLOGY

The simulation that will be used in this research assignment is the Milky Way and Andromeda major merger event. There are 800 snapshots for both Milky Way and Andromeda that spans across 11 billion years in the dataset. Each snapshot contains datapoints regarding the time, position coordinates, and velocity coordinates of their corresponding galaxy. However, for the purpose of achieving the project goals, the paper will consider 4 snapshots with snapnumbers of 0, 350, 455, and 801 as they resemble key stages throughout the major merger event.

The research project will attempt to answer the specified questions above using sections of python code from the course homework and labs. Since we are focusing on dark matter halo aspect of the galaxy, particle type = 1 will only be considered in both galaxies data file. Both Milky Way and Andromeda are to be modeled as Hernquist profiles before the collision. Homework 6 will be used to provide insights on when the merger event occurs along with when both galaxies settle into one merger remnant. This will help locate the time and corresponding snapshot number for the initial and final conditions of the system. In reference to Lab 6, the merger remnant density profile will be plotted along side the Hernquist profile to compare the difference between the initial and final state. For the concentration, the research assignment will obtain the concentration parameter for both initial and final merger state based on the information of their corresponding density profile.

The computational calculations to consider in this research project are computed through Python codes. To achieve the final density of the merger remnant, the MassProfile function from Homework 6 will need to be modified to take into account of 2 galaxies, that is the Milky Way and Andromeda. Then, selecting the a snapnumber that corresponds to when the separation of Milky Way and Andromeda is zero in the plot, the function will output the Mass Profile of the halo merger remnant.

$$\rho = \frac{M_{halo}}{V}$$

$$\rho_{Hernquist} = \frac{M_{halo}}{2\pi} \frac{a}{r(r+a)^3}$$

where M_{halo} is the mass of the merger remnant halo, V is the volume of the merger halo, a is the Hernquist scale length, r is the radius. Using the formulas above, the general density and Hernquist density of the halo merger remnant can be obtained. To find out if the final density of the system has changed from its initial density, the paper will overplot the initial Herquist density with the general denisty and Hernquist density of the merger remnant computed earlier. The denisty overplots will show if self similar evolution is produced as described in Drakos et al 2019.

$$\rho_{crit} = 1.617 * 10^2 \frac{M_{sun}}{kpc^3}$$

The critical density value which is defined to be the minimum density required to maintain a flat universe. The edge of the merger remnant halo, R_{200} is 200 times the critical density, ρ_{crit}. With this information, the edge of the halo over different points in major merger event can be determined. The concentration of the dark matter halo in the remnant will be determined using the concentration parameter as defined in the introduction.

To elaborate on the plots that will be constructed in this research project, the final halo density of the major merger remnant can be compared to any type of density profile through overplots in a logarithmic density vs radius graph. The key density profile to set side by side with is the initial Hernquist density profile of the Milky Way and Andromeda. In another plot, the critical density value is multiplied by 200 and will be overplotted into various density profiles of the merger remnant in different snaphots. The point where the corresponding density profile and the critical density intersects in the graph will reveal the edge of the dark matter halo remnant, R_{200}

My prediction is that the final density profile of the merger remnant is to be settled relatively similar to the initial density profiles of both galaxies due to self-similarity evolution. Therefore, the merger remnant should show only subtle differences when compared to the initial Hernquist profile. It is difficult to predict how much concentration change between the initial and final state would have. However, it is trivial to think that merger remnants would have a higher concentration than the state before they merged.

4. RESULTS

Major Merger Event	$R_{200}(kpc)$
Snapnumber, 0	115.352
Snapnumber, 350	119.159
Snapnumber, 455	134.639
Snapnumber, 801	136.293

Table 1: The edge of the halo remnant, R_200 in snapnumbers 0,350,455,801

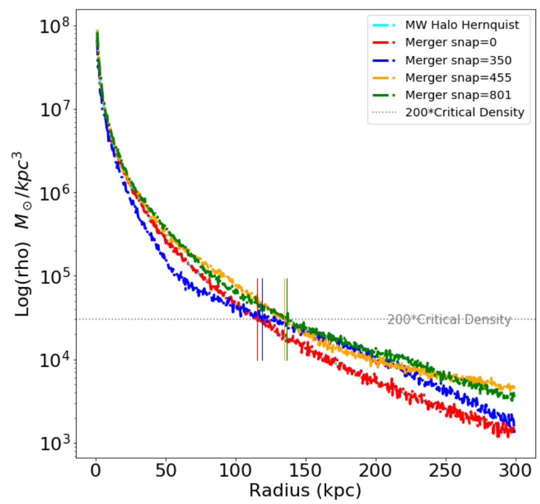

Figure 3: The plot of the evolution of the Measured Halo Density Profile from snapnumbers 0,350,455,801 in reference with the Theoretical Halo Hernquist Model. The vertical lines depicts the corresponding snapnumbers halo edge, R_{200}

In Figure 3, the measured Local Halo Density for 4 different key stages of the simulation data is shown with respect to the Theoretical Hernquist Local Halo Density Profile of the Milky Way in a density vs radius plot. As expected, the Measured Halo Local Density at snapnumber 0 is well align with the Theoretical Hernquist Halo Density Profile of Milky Way. Snapnumber 0 of is taken from the simulation data of Milky Way only. The following 3 stages all indicate deviations from the theoretical Hernquist model. As time increases in the Milky Way and Andromeda simulation data, the larger the deviations as illustrated in Figure 3. The curve colored in green shows the final halo density of the Milky Way and Andromeda merger galaxy. A horizontal line across the density value of 30348 $\frac{M_{sun}}{kpc^3}$, signifies 200 times the critical density. The intersection of the 4 Measured Local Halo Density Profiles with 200 times critical density indicates edge of the halo remnant, R_{200} with their respective time event.

Based on Table 1, the radius of the halo remnant increases throughout the the major merger event.The edge of the halo merger remnant grew almost 21 kpc in radius according to the simulation analysis. The key observations from Figure 3 is the evolution of the Milky Way and Andromeda halo density, accompanied with the calculations of the increasing radius trend using the simulation data expressed in Table 1.

The scale length for 4 different key stages of the simulation data is estimated through the best fit between the Theoretical Hernquist Mass Profile and the Total Halo Mass Profile of the galaxy. In Figure 4a illustrates the best fit between the mass profile given by a specific scale length,a for each of the 4 key stages of the major merger event. Snapnumber 0 and 350 only takes into account of the Milky Way's halo mass, whereas, snapnumber 455 and 801 takes the sum of Milky Way and Andromeda's halo mass.

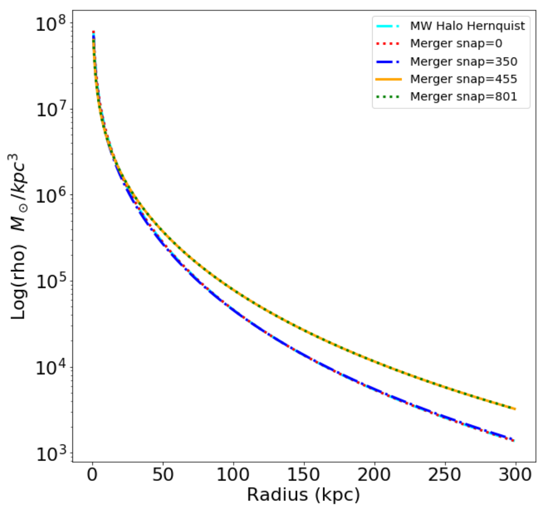

Figure 4b: The plot of the Theoretical Halo Hernquist Density of snapnumbers 0,350,455,801 using the scale lengths obtained from Figure 4a. The curves are overplotted in reference to the Theoretical Halo Hernquist Model of the Milky Way.

As a result, Figure 4b shows the Theoretical Hernquist Halo Profile with the scale lengths,a from Figure 4a plotted with respect to the Theoretical Hernquist Profile of the Milky Way. Based on Figure 4b, snapnumber 0 and 355, both indicating the events prior to the major merger event has shown a well fitted curve with the Theoretical Hernquist model. However, snapnumbers 455 and 801 which resembles the timeline during and after major merger event shows deviation away from the Theoretical Hernquist model. Based on the results, it can be concluded that the Milky Way and Andromeda system in terms of their dark matter halo follows the Theoretical Hernquist model before collision.

The concentration of the dark matter throughout 4 key stages of the Milky Way and Andromeda simulation data is calculated by the Concentration Parameter formula as described in the Introduction. Table 2 shows the value of Concentration Parameter for the corresponding 4 snapnumbers. It shows that the events from before and during collision declines in their dark matter concentration parameter. However, as the halo merger remnant settles into its final density, it exhibits a slight increase in its Concentration Parameter.

Major Merger Event	c
Snapnumber, 0	1.891
Snapnumber, 350	1.833
Snapnumber, 455	1.374
Snapnumber, 801	1.391

Table 2: Concentration Parameter,c in snapnumbers 0,350,455,801

5. DISCUSSION

Based on the results of Figure 3, there is a clear deviation of the final halo density profile from the initial halo density profile that is the Theoretical Hernquist model. The initial hypothesis is that there is only a subtle difference at small radii and followed by a distinct deviation away from the initial halo density profile. The hypothesis seems to agree with the results that was obtained and displayed on Figure 3. Also, Figure 2 and Figure 3 together illustrated both initial and final halo density profile as very similar in small radii and only branching off slightly at larger radii. Even though different density profile were considered in Figure 2 and Figure 3, the repercussions of the major merger event yields a relatively similar result. With that, this points towards the

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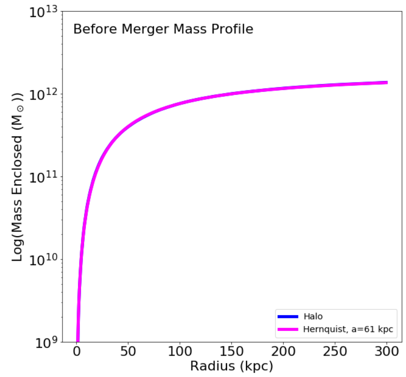
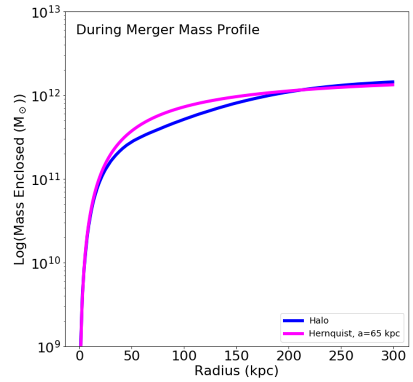
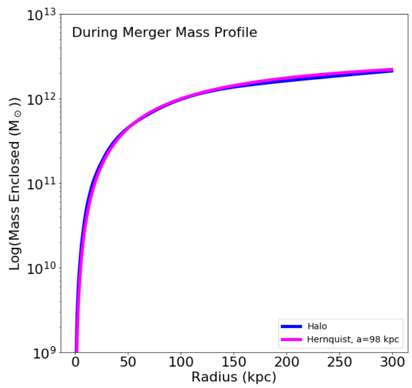


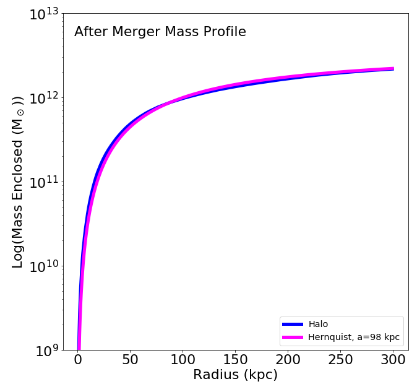
(a) Snapnumber 0, a = 61 kpc



(b) Snapnumber 350, a = 65 kpc



(c) Snapnumber 455, a = 98 kpc



(d) Snapnumber 801, a = 98 kpc

Figure 1: Best fit of Mass Profile of the Milky Way for (a) and (b) and the merger for (c) and (d) between its total halo mass and the halo Hernquist model at their corresponding snapnumber and resulting scale lengths