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Analyzing the Density Profile Evolution of the Dark Matter Halo Remnant of the MW-M31 System

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ABSTRACT

The density profiles of the dark matter halos and their evolution are examined in terms of two theoretical profiles: the Hernquist (Hernquist 1990) and Navarro-Frenk-White (Navarro et al. 1996) profiles. The comparison of these profiles to the density density profile of simulated dark matter halos of the MW-M31 system at different points in their merger can provide an insight into the dynamics and structure of the dark matter halos surrounding these galaxies. In order to determine the best-fit profile for each stage in the evolution (particularly the final stage), a difference parameter is taken and attempted to be minimized. While the optimization did not provide ample time to calculate accurate results, it seems that throughout the evolution of the dark matter halo of each of the M31 and MW galaxies, the Hernquist profile best fit the simulated data. Should time allow for a deeper investigation into the optimization of the Hernquist and NFW parameters (scale radius and scalar density), a possible discover of a scale factor addition needed to accurately describe the profile predictions, or a discovery of support of a profile by the data perfectly fitting it may be found.

Keywords: Major Merger[a], Cold Dark Matter Theory[b], Hernquist Profile[c], Dark Matter Halo[d], Merger Remnant[e]

1. INTRODUCTION

It is predicted that in approximately 5.86 Gyrs, our galaxy, the Milky Way (MW), will collide with the Andromeda Galaxy (M31) in a major merger (van der Marel et al. 2012), where the two galaxies will collide and coalesce. While the dark matter halos, the encompassing collection of dark matter, of each galaxy are not directly visible, they are vital to our current understanding of cosmological formation since they are the cradle for all visible galaxy formation in the universe. Dark matter halos interact gravitationally with visible matter, and thereby completely envelope visible matter. Mergers such as the MW-M31 merger can have a major effect on the structure of the dark matter halo, specifically its shape and concentration, and provide a unique opportunity to examine these galactic cradles in their evolution as they combine (Drakos et al. 2019a). The concentration of the dark matter halo is defined as defined as $\frac{R_{200}}{R_{scale}}$ where R_{200} is the radius where the dark matter halo density is 200 times the critical density to close the universe $\rho_{crit} = 1.62 * 10^11$ Msun Mpc^{-3}, and R_{scale} is the scale length of the Hernquist Halo Profile. The Hernquist Profile is an analytical expression for dark matter density distribution in galaxies,the dark matter density at a given radius r is given by $\rho(r) = \frac{M}{2\pi}\frac{R_{scale}}{r}\frac{1}{(r+R_{scale})^3}$ where M is the total dark matter halo mass and R_{scale} is the scale length (Hernquist 1990). Another dark matter halo profile commonly used is the Navarro-Frenk-White (NFW) profile, given by $\rho(r) = \frac{\rho_s}{\frac{r}{R_{scale}}*(1+\frac{r}{R_{scale}})^2}$ where ρ_s is the scale density of the halo (Navarro et al. 1996). In order to better understand the evolution of the dark matter halo remnant of the MW-M31 system in terms of the density profile through simulation, the halo density profile was compared to well known dark matter profiles. These findings could

[a] The coalescence of two (or more) galaxies of comparable size

[b] A proposed theory of dark matter in which dark matter particles interact primarily though gravity and are slowly moving in comparison the the speed of light

[c] A dark matter halo density profile of $\rho(r) = \frac{M}{2\pi}\frac{a}{r}\frac{1}{(r+a)^3}$ as given by Hernquist (1990)

[d] A proposed collection of dark matter particles that envelopes a galaxy, group, or cluster

[e] The particles (baryons and dark matter) that remain after two (or more) stellar collections coalesce

help shed light upon the structure of dark matter and the formation and evolution of dark matter halos through hierarchical processes like galaxy mergers.

Dark matter is an unknown substance, proposed to only interact gravitationally by Cold Dark Matter (CDM) Theories, which is meant to account for the absence of enough visible matter to provide ample gravitational force to bind galaxies together. On large scales, dark matter tends to cluster into filaments, and it is the intersection of these filaments (where the density is higher) that are known as 'halos'. These halos are the exclusive site of galaxy, group, and cluster formation. As defined by Willman & Strader (2012), a galaxy is a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons (gas, dust, and stars) and Newton's laws of gravity. An understanding of dark matter halo structure and evolution is essential in order to understand cosmology and galactic evolution, the change in the properties of a galaxy over time. (Drakos et al. 2019b).

While some information of dark matter halos can be observationally determined, through means of galaxy kinematics, satellite kinematics, and gravitational lensing, numerical simulation accounts for most of the detailed knowledge of dark matter halos (Drakos et al. 2019a). Halos form in a hierarchical manner, small structures combining with larger ones. (Frenk & White 2012) There are two common density profiles that are understood to describe physical dark matter halo density profiles well: the Navarro-Frenk-White (NFW) profile (Navarro et al. 1996) and the Hernquist profile (Hernquist 1990). Along with other explanations of dark matter density distributions, these profile provide insight into the underlying physics and dynamics of dark matter halos. Figure 1 shows the comparison of these distinct dark matter profiles with simulated data.

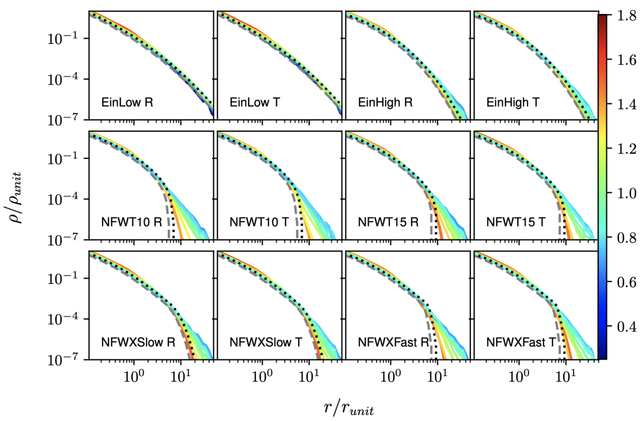


Figure 1: Density profiles of dark matter halo remnants for the Einasto (Einasto 1965) and NFW profiles with distinct parameters as to distinguish their parameter dependence (Drakos et al. 2019a). The grey dashed lines show the initial halo models, while the black dotted lines are shown for specific initial conditions with the radius being rescaled by a factor of 21/3. The T and R labeled on the plots indicates whether the initial velocity was tangential (T) or radial (R). The coloration depicts the relative energy change of the remnants. Notice the differences both the profile and the parameters of each profile make when fitting a halo density profile.

Although the NFW and Hernquist profiles are commonly used theoretical profiles, they are not definite explanations of the density profiles of any and every dark matter halo. These profiles could prove to be incorrect under specific circumstances or not quite fit the data altogether. An inquiry into these profiles can provide much needed information into the nature of dark matter. Many purse investigation into these models by comparing them under certain conditions (profile parameters) and seeing where these profiles disagree (Drakos et al. 2019a).

2. THIS PROJECT

In this project, we will explore the evolution of the dark matter halos of the MW and M31 in terms of their density profile and shape as they approach each other and eventually merge. The density profile will be analyzed at three different times during the galaxy merger: when the two galaxies are far apart (present day), when the two galaxies are significantly close (about 3.87 Gyr), and when the galaxies finally merge (in roughly 5.86 Gyr) (van der Marel et al. 2012). At each snapshot, the dark matter halo profiles of the MW and M31 will be analyzed with respect to their radius and fit to a Hernquist and NFW profile by way of an optimization of the Hernquist and NFW scale parameters.

The comparison of the halo profile to the Hernquist and NFW profile will show variations between the profiles, and show which of the theoretical profiles, the Hernquist or the NFW profile, that best fit each galaxy at that stage in its evolution.

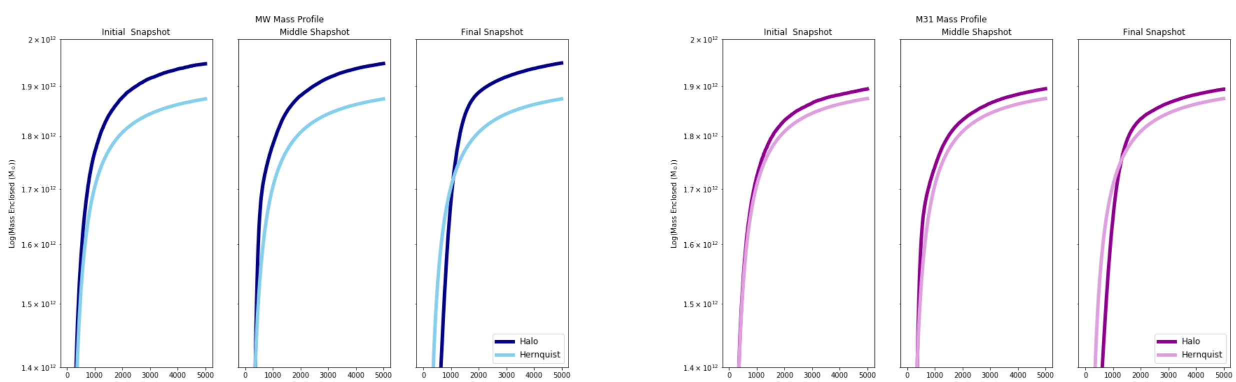
Along with the evolution of the dark matter halo, this project is concerned with studying the final density profile of the MW-M31 system. The final density profile will be compared to a Hernquist profile. (Hernquist 1990). The NFW profile will be compared to the Hernquist profile in an attempt to better understand the density profile of the eventual dark matter halo remnant. A better understanding of the NFW and Hernquist profiles can be built by testing and optimizing their parameters to fit the simulated data (van der Marel et al. 2012). Should a scale factor be needed to best fit the data, a new description of the profile would be needed. Should the optimization prove that the optimal parameters of the profiles are those exactly described by their definitions, this project will result in the support of the profile and its description.

As dark matter is not well understood, information about the evolution of the dark matter halo of the MW-M31 system could prove to be useful in developing our understanding. Comparing simulated data to the theoretical profiles is currently the best of these theories, and therefore can support or oppose the theory behind the dark matter profile.

3. METHODOLOGY

In using the simulated data of the dark matter halo of both the MW and M31 during their eventual merger (van der Marel et al. 2012), the density profile of the halo could be compared to the Hernquist and NFW theoretical profiles. The simulated data is a result of an N-body simulation in which a system of particles are observed to interact as an investigation into their dynamics and structure.

The simulated data of each the MW and M31 are analyzed to determine their respective dark matter halo's density profile. The simulated profile is then compared to the NFW and Hernquist profile by way of a χ^2 test. The parameters of the NFW and Hernquist profiles are adjusted in an optimization function as to minimize the χ^2 value, which provides the "best" fit of the theoretical profile to the simulated data. As this optimization method would run for quite a while, time did not allow for precise optimization of the parameters, but only a rough approximation. In considering the mass profiles of each galaxy, as shown in Figure 2, the optimization function should reduce the distance between the two curves. Knowing the optimized parameters will give information about the profiles themselves and the evolution of the halos of the galaxies. Figure 2 describes the mass profile with respect to galactic radius for M31 and the MW at different stages in the evolution of their merger. The profile's variables are identical to those used above. As the galaxies evolve, their mass profile evolves as well, indicating a need to adjust the parameters of the Hernquist profile.



(a) The mass profile of the MW

(b) The mass profile of M31

Figure 2: The mass profiles of the MW and M31 dark matter halos. The calculated density of the dark matter halo is plotted with the Hernquist profile (of scale radius 62 kpc and halo mass $1.921 * 10^{12}$ M_{sun}/kpc). The y-axis is the Log(Mass Enclosed M_{sun}) and the x-axis is the radius. The Hernquist profile best fits the data in the initial snapshot, but as the galaxies evolve, the Hernquist profile has a larger difference from the data. Hernquist (1990)

The Hernquist Profile at a specific radius, r, is given by

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

where M is the total dark matter halo mass (M_{sun}) and R_{scale} is the scale length (kpc) (Hernquist 1990). The Navarro-Frenk-White (NFW) profile, differs from the Hernquist profile in that it is given by

$$\rho(r) = \frac{\rho_s}{\frac{r}{R_{scale}} * (1 + \frac{r}{R_{scale}})^2}$$

where ρ_s is the scale density of the halo ($\frac{M_{sun}}{kpc^3}$) (Navarro et al. 1996). These profiles are calucalted at multiple radii and compared to the simulated data by means of a χ^2 test, defined as

$$\chi^2 = \frac{1}{d} \sum_{k=1}^{n} \frac{(O_k - E_k)^2}{E_k}$$

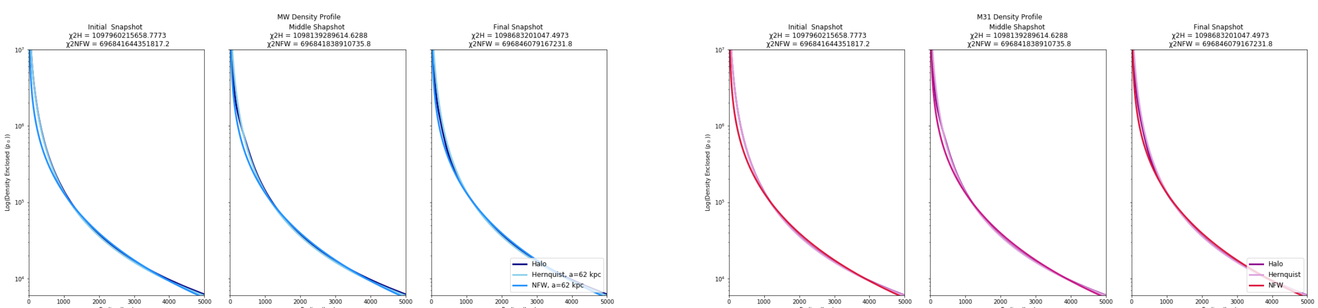
where O_k is the value of the theoretical profile (Hernquist or NFW) at a specific radius and E_k is the value of the simulated halo density at that radius. This value is minimized though the optimization procedure as to reduce the difference between the theoretical profiles and the simulated profile.

The density profiles will be examined in three ways: in terms of their mass versus radius, their density versus their radius, and the residual density ($\mid O_k - E_k \mid$) as correlated to their radius. The mass profiles (Figure 2) will provide a more immediate physical meaning of the profiles, showing how the mass of the dark matter halo is dependent on the radius enclosing it. Due to discrepancies, only the Hernquist profile is shown in Figure 2. The density profile shows the similarities between the two profiles and the simulated data, while also indicating where they disagree. The residual density plot indicates where and by how much the theoretical profiles disagree with the data; a visual measure of fitness, in a way.

4. RESULTS

Figure 3 shows the density profile with respect to galactic radius for the MW and M31 galaxies as they merge. The data provided is shown in comparison to the Hernquist and NFW profiles. The NFW profile relies on two variables, the scale radius, $R_{scale} = 2400$ kpc, and the density scalar, $\rho_0 = 1.1 * 10^5\ M_{sun}/kpc$. The Hernquist profile also relies on two parameters, the scale radius, $R_{scale} = 62$ kpc, and the total halo mass, $M_{halo} = 1.921 * 10^12\ M_{sun}/kpc$. The two parameters are optimized so that the χ^2 value is minimized when compared to the data provided. It appears that the Hernquist profile best fits both the MW and M31 in their initial states, but the NFW profile becomes more similar to that of the halos in the final snapshot.

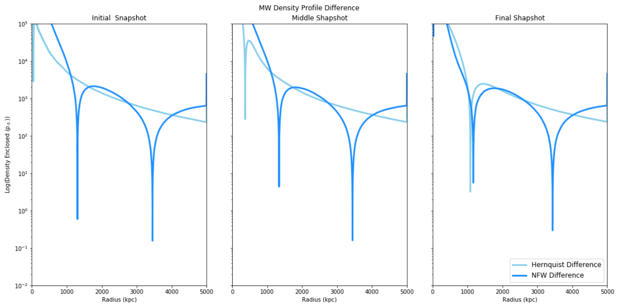
Figure 4 indicates the differences between the profiles and the simulated data by plotting the residual density ($\mid O_k - E_k \mid$ where O is the theoretical profile and E is the simulated data) against the radius enclosing that density. This shows how well-fit the profiles are to the simulation data, and can point out possible places for improvement through choosing the profile parameters.



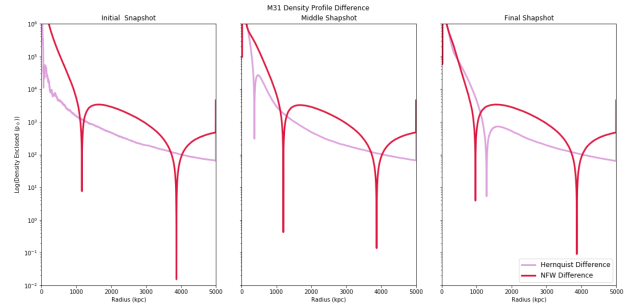
(a) The density profile of the MW

(b) The density profile of M31

Figure 3: The density profiles of the MW and M31 dark matter halos. The calculated density of the dark matter halo is plotted with the Hernquist profile (of scale radius 62 kpc and halo mass $1.921 * 10^{12}\ M_{sun}/kpc$), and the NFW profile (of scale radius 2400 kpc and density scalar $1.1 * 10^5\ M_{sun}/kpc^3$). The χ^2 value for the Hernquist profile and the NFW profile are given by χ2H and χ2NFW, respectively, for each snapshot. The y-axis describes the Log(Density Enclosed (M_{sun}/kpc)), while the x-axis describes the radius (kpc). Notice that the Hernquist profile best fits the profiles in the initial snapshot, but the NFW improves as the two galaxies merge Hernquist (1990) and Navarro et al. (1996)



(a) The residual density profile of the MW



(b) The residual density profile of M31

Figure 4: The residual density profiles of the MW and M31 dark matter halos when compared the simulated data. The Hernquist profile parameters used were a scale radius of 62 kpc and a halo mass of $1.921 * 10^{12}$ M_{sun}/kpc), while the NFW profile parameters were of scale radius 2400 kpc and a scalar density of $1.1 * 10^5$ M_{sun}/kpc^3). The y-axis shows the Log(Density Enclosed (M_{sun}/kpc)), while the x-axis depicts the radius (kpc). Note that the NFW crosses the simulated density profile twice, indicating that an optimized parameter may be needed. Hernquist (1990) and Navarro et al. (1996)

5. DISCUSSION

Figure 3 visually indicates that the mass profile of both M31 and the MW diverges from the Hernquist profile that was well fitted in the initial snapshot. The Hernquist profile χ^2 value confirms this as it is lowest in the initial snapshots of both galaxies. This suggests that the parameters of the Hernquist profile (the scale radius, a = 62 kpc, and halo mass $M_{halo} = 1.921 * 10^{12}$ M_{sun}/kpc) should be varied as the galaxies evolve, as the scale radius and the total mass are changing.

Similarly, Figure 4 shows the correlation between the dark matter halo density profile and the Hernquist profile at the initial snapshot. As these galaxies evolve, their profiles evolve somewhat toward an NFW density profile. The NFW profile crosses the simulated density profile curve twice, suggesting that it may not have optimized parameters, which requires further investigation. While the Hernquist profile residuals stay approximately the same though the galaxies' evolution, it is apparent that the NFW profile residual changes. An examination of optimization of the parameters of both the Hernquist and the NFW profiles will be continued to discover which profile best fits each galaxy at each stage in its evolution. With such large residuals currently, neither profile fits the simulated data considerably well.

6. CONCLUSION

The dark matter halo density profiles of the M31 and MW galaxies were examined at a early, middle, and late time period in their evolution, with each compare to the the Hernquist (Hernquist 1990) and Navarro-Frenk-White (Navarro et al. 1996) profiles. This comparison reveals the areas of agreement between the simulated dark matter halo density and the Hernquist and NFW density profiles.

By the preliminary results, it seems that a Hernquist profile best fits the dark matter halo density profiles, especially after the merger is complete, as indicated by the minimized χ^2 value when compared to the initial and subsequent time period. The ultimate merger of the MW-M31 system is best fit by a Hernquist profile according to the findings. Although this may change upon improved parameter (scale radius and scalar quantity) optimization.

An investigation into the optimum parameters in which the χ^2 values are minimized will be continued. With the accurate values of the density profiles, the Hernquist and NFW profiles may be found to need a scalar or may be found to be accurate from their physical description. This would also provide information on the simulation the dark matter halo and uncover possible methods of improvement.

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Software: Astropy (Astropy Collaboration et al. 2013), Matplotlib (Hunter 2007), numpy (van der Walt et al. 2011), scipy (Virtanen et al. 2020), ipython (Pérez & Granger 2007)

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Drakos, N. E., Taylor, J. E., Berrouet, A., Robotham, A. S. G., & Power, C. 2019a, MNRAS, 487, 993, doi: 10.1093/mnras/stz1306

—. 2019b, MNRAS, 487, 1008, doi: 10.1093/mnras/stz1307

Einasto, J. 1965, Trudy Astrofizicheskogo Instituta Alma-Ata, 5, 87

Frenk, C., & White, S. 2012, Annalen der Physik, 524, 507–534, doi: 10.1002/andp.201200212

Hernquist, L. 1990, ApJ, 356, 359, doi: 10.1086/168845

Hunter, J. D. 2007, Computing in Science & Engineering, 9, 90, doi: 10.1109/MCSE.2007.55

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563, doi: 10.1086/177173

Pérez, F., & Granger, B. E. 2007, Computing in Science and Engineering, 9, 21, doi: 10.1109/MCSE.2007.53

van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012, The Astrophysical Journal, 753, 9, doi: 10.1088/0004-637x/753/1/9

van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, Computing in Science Engineering, 13, 22

Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261, doi: https://doi.org/10.1038/s41592-019-0686-2

Willman, B., & Strader, J. 2012, The Astronomical Journal, 144, 76, doi: 10.1088/0004-6256/144/3/76