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Kinematic Contributions to the Milky Way – M31 Halo Major Merger Remnant Structure

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1 INTRODUCTION

Dark matter, although yet to be identified, is now considered to be an essential part of the universe, surrounding galaxies in a structure called a **dark matter halo**. The need for a dark matter halo model became apparent in the last century when observational evidence showed that more mass was needed beyond baryonic matter for spiral galaxies to be stable (Ostriker et al. 1974). This, along with the fact that Newtonian gravity fails to explain the observed galactic dynamics, led Willman & Strader (2012) to define a **galaxy** as *a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity*. Over the past decades, advances in computation and simulations have revealed to us ever finer details in halo structure. Among these simulations, galaxy merger simulations are particularly useful for studying how certain galaxies are structured the way they do today, as mergers happen frequently in the universe. For example, **major mergers**, which are mergers of two galaxies of similar mass, explains our observations of irregular and starburst galaxies (cite?).

Studying how halo structure changes through a major merger can help us understand **galaxy evolution**, which is how galaxies form and change over time. Specifically, understanding the structure of individual haloes and how they change through mergers can greatly inform us about the merger history of the galaxies we observe. In our observations, we only see one snapshot of a galaxy, so simulations are a good way for us to study how galaxies evolve and allow us to map each observed galaxy to a stage in its evolution. This work will be done using an N-body simulation of the Milky Way (MW)-M31-M33 system by van der Marel et al. (2012).

The connection between merger history and the resulting halo structure has been extensively studied. For example, major mergers, as opposed to minor mergers (ones where one halo is much less massive than the other), have been found to bring more material to the halo center, allowing for more homogeneous mixing (Frenk & White 2012). Past studies using merger simulations have found major connections between orbital parameters and the resulting halo shape (Drakos et al. 2019a), as well as between the energy of the merger encounter and the final mass distribution (Drakos et al. 2019b). In another simulation study, Abadi et al. (2010) demonstrated that haloes become more axisymmetric through mergers. As shown in Figure 1, Drakos et al. (2019b) also provides the interesting result that the virial mass of the merged halo is not merely the sum of the virial masses of the initial haloes. The virial mass is the mass enclosed within the **virial radius** (r_{vir}), which is strictly defined as the radius within which the virial theorem applies. However, for this work, I will define v_{vir} to be the radius within which the enclosed dark matter density is 360 times that of the universe.

On the matter of halo mergers, further work could be done in exploring a wider variety of mergers, as studies like Drakos et al. (2019a) only explored mergers of identical haloes. After all, the vast majority of mergers in the universe are minor mergers, so they account for the formation of a larger fraction of the galaxies we observe. For instance, minor mergers could help explain the open question left by Drakos et al. (2019b), which is that the central density in haloes seem to drop as they grow in size. With major mergers, however, there is also more interesting physics to be explored. It is still unclear how in major merger simulations, the central concentration seems to increase rather than decrease (Drakos et al. 2019b). Another area of study is the contribution of each progenitor halo in the spin, shape, and matter distribution of the merger remnant, which is what we will be exploring in this work. This paper is organized as follows: In Section 2, we motivate the specific question that will be explored. In Section 3, we describe the computational and analysis methods used for this project. In Section 4 we present the results. We discuss the results and conclude in Section 5.

2 THIS PROJECT

In this paper, we will study the contributions of MW and M31 halo particles to the density profile of the merged remnant. It will be interesting to explore the distribution of halo particles from both MW and M31 within the merged remnant to see if either system contributes more at a certain radii. It will also be interesting to compare the fitted density profile parameters of the progenitors and the merged remnant to see if the properties of the merged system reside somewhere between the two systems or are vastly different from both. Following Drakos et al. (2019b), We will also explore how the virial radius of the halo changes after merger, and explore its relationship with the energy components of the system.

This work will mark as part of the exploration into how each major merger halo contribute to the merged system, as mentioned in Section 1. Specifically, we are exploring the matter distribution of the haloes by computing and comparing density profiles.

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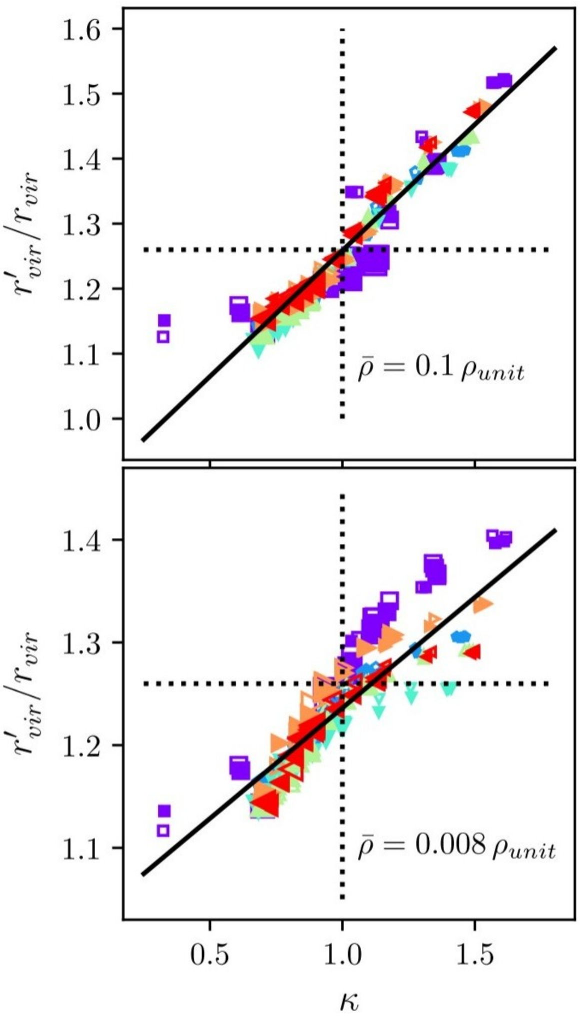

Figure 1. The change in virial radius r'_{vir}/r_{vir} as a function of the relative energy change κ. Virial mass scales as r^3_{vir}, so this figure also shows a wide distribution in mass scaling after merger despite starting with two equal mass haloes. Figure taken from Drakos et al. (2019b). The meanings of the colors and symbols are described in the paper, however they are not relevant to this work.

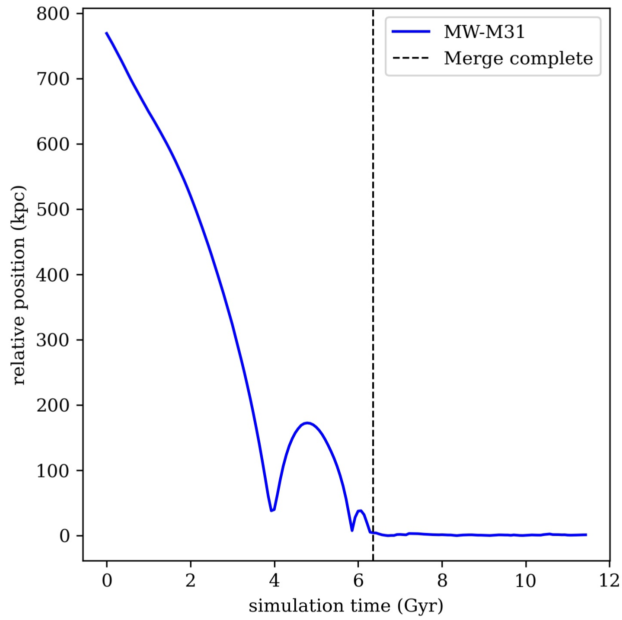

Figure 2. The relative positions of the center of masses of MW and M31 over the course of the simulation. After the black dashed line, the relative position effectively flattens, showing that the two systems have merged.

Understanding the intricacies of merger contributions is important, as it could allow us to better infer kinematic and merger histories of haloes from observations of their current state. Using the MW-M31-M33 system as a case study, this work will demonstrate how various initial halo properties could cause subtle differences in contribution to the density profile of the merged halo.

3 METHODS

For this project, I will be using the N-body simulation for the MW-M31-M33 system described in van der Marel et al. (2012). An N-body simulation is a numerical simulation of many particles in a physical system. This simulation models the initial conditions of the system consistent with current measurements, and models each galaxy using three types of particles: halo, disk, and bulge. The distribution of halo particles for each galaxy follows a **Hernquist Profile** (Hernquist 1990), which is a halo profile whose density function $\rho(r)$ has the form

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}(1 + \frac{r}{r_s})^3}, \tag{1}$$

where r is the radius from center of halo, and ρ_s and r_s are scale density and radius parameters that are fitted for each galaxy. The disk and bulge of each galaxy follows exponential profiles, whose parameters follow past literature, and M33 is taken to be bulgeless.

For this study, we will only be using the halo particles in the simulation. We will also be using a few snapshots of the simulation at the highest resolution (HighRes), as we are only comparing before and after merger states, not studying the evolution of the system over time. The initial comparison of density profiles will be made using the first and last snapshots of the simulation (0 and 801). As analysis continues, we might need to use snapshots closer to the merge event (i.e. close to the first pericenter or just after merge completes) to get a better idea of how energy transfers in the system through the merger. The relevant snapshots can be easily identified by plotting the relative positions of MW and M31 over all the snapshots, as shown in Figure 2. The first pericenter is the first local minima in the plot, and we defined the merged state as the snapshot after which the distance between the center of masses of MW and M31 is less than 5 kpc. As the steps for this study depends on the results of the previous step, we show a decision tree in Figure 3 to illustrate the process. This work will be limited to only analyzing density profiles and the energy components of the system.

To find the contributions of MW and M31 halo particles in the density profile of the merged system, I will plot the density profiles of both systems at the last snapshot individually and then over-plot the sum of their profiles for the profile of the merger remnant. To compute the density profile, we will first compute the enclosed mass profile $M_{enc}(r)$ for a set of radial bins R_i, by simply summing the masses of all the particles contained within R_i. After that, the density ρ_j between bins R_i and R_{i+1} can be calculated by

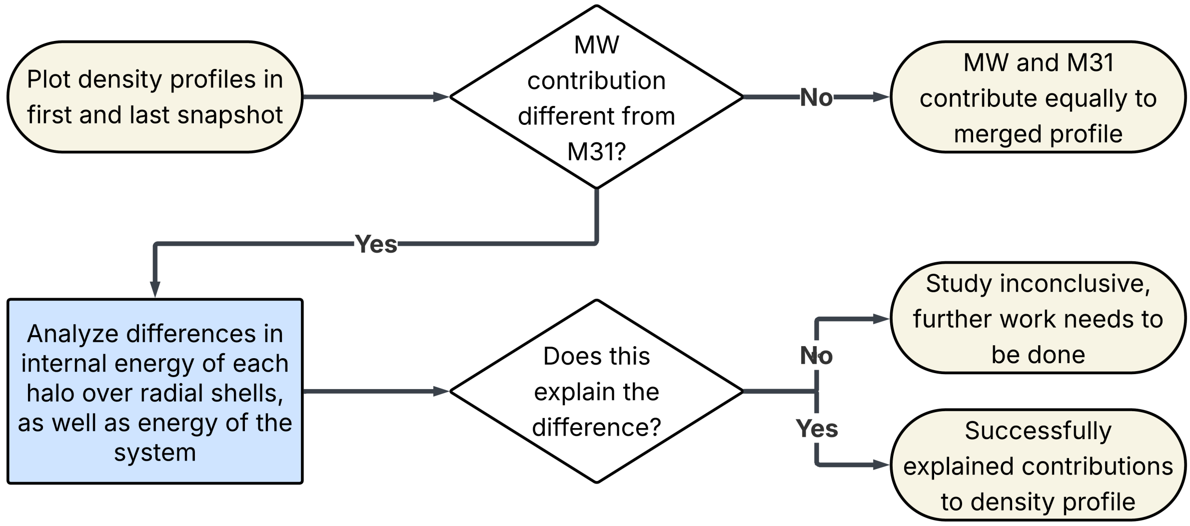

Figure 3. Decision tree illustrating the research process for this work.

$$\rho_j = \frac{M_{enc,i+1} - M_{enc,i}}{V_{enc,i+1} - V_{enc,i}}, \tag{2}$$

where

$$V_{enc,i} = \frac{4}{3}\pi R_i^3. \tag{3}$$

The radii r_j at which the density is ρ_j is then

$$r_i = \frac{R_{i+1} + R_i}{2}. \tag{4}$$

Then, I will compare the halo density profiles of the merged system and the individual systems. I will model using the NFW profile (Navarro et al. 1997):

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}(1 + \frac{r}{R_s})^2}, \tag{5}$$

where ρ_0 and R_s are free parameters that will be fitted for each halo. For simplicity, I will use the curvefit function in the SciPy Python package to fit the profile. The NFW profile strikes a good balance between simplicity and physicality, which makes it an ideal model to compare density profiles before and after merger.

Next, I will compare the spin axis orientations. Lab 7 of this course contains code that computes the angular momentum vector of a set of particles, which is synonymous with spin axis orientation; I will use this code to compare orientations of individual haloes and the merged system.

Lastly, I will compare the virial radius of the individual haloes and the merged system, following the analysis of Drakos et al. (2019b). I define the virial radius r_{vir} as the radius at which the dark matter density is 360 times the average dark matter density of the universe, as explained in lecture 10. Given that the MW and M31 haloes are similar in mass, I will compute the ratio between the radii of the merged system and the individual halos, r'_{vir}/r_{vir}, and compare it with Figure 1 to see if the merged system gains or loses internal energy from the merger. I will also compute the enclosed mass within the virial radius of all systems to see if the merged mass is the sum of the individual halo masses.

3.1 Hypothesis

Because the haloes of MW and M31 in the simulation are similar in size, I expect them to have near equal contribution to the final density profile, meaning that the halo particles from MW and M31 will be equally distributed throughout the remnant halo. I expect the NFW profile parameters to be vastly different for the merged system compared to the individual haloes, as the shape of the galaxy changes dramatically through the merger (elliptical vs. spiral). I also naively hypothesize that the orientation of the spin axis for the merged system will be somewhere in between the spin axes of MW and M31. Lastly, as Drakos et al. (2019b) suggests, I don't expect the mass enclosed in the virial radius of the merged system to be a mere sum of those of individual haloes.

4 RESULTS

5 DISCUSSION

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