Testing the behavior of Satellite M33 After Major Merger

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ABSTRACT

The kinematics of a galaxy is crucial to defining it and understanding how it works; among many characteristics, the escape velocity of a galaxy is very important as it sets the speed limit that an object can have before it becomes unbounded to the galaxy. This report uses simulation data from van der Marel et al. (2012), which modeled the merger of the Milky Way and Andromeda (M31) galaxies. Our main goal was to see if we can expect M33 to remain bounded to the merged remanent of M31 and the Milky Way or if it would be ejected out of the system. We find that M33 is expected to remain bounded to the system. While M33 will stay bounded, other galaxies may not, understanding the role a galaxies escape velocity has in determine the amount of bounded satellites can shed light on the discrepancies in observational vs theoretical data otherwise known as the missing satellites problem.

Key words: Galaxy,Satalite Galaxies Escape Speed, Dark Matter Halo, Hernquist Profile, Major Merger, Star Burst, Missing Satellites Problem

1 INTRODUCTION

1.1 The Topic

The kinetic evolution of the Dark matter halo after a major merger is described by how objects in the halo move and how that movement changes through the merging process. The **Dark matter halo** is a virialized distribution of dark matter that is decoupled from the expansion of the universe Privet communication, Besla, May 2025. This region is dominated by non-visible dark matter as the name suggests and is crucial to maintaining the galaxies internal structure. In galaxy mergers the halo governs over the orbital dynamics and is what drives the eventual combining into one singular galaxy remanent.

1.2 Why it Matters

Galaxies are defined as a gravitationally bound set of stars whose properties cannot be a combination of baryons and Newton's Laws of gravity Willman & Strader (2012). One aspect of galaxies are the satellites that orbit around them. **Satellite Galaxies** are smaller galaxies that are bound to a larger galaxy like how the moon is bound to Earth. These satellites accompany the larger galaxies through out it's life span but if the larger galaxy experiences a major merger, the bound state of the satellite is at risk. A **Major Merger** is an event where two large galaxies collide and become one. Major mergers change the Kinematics of the two galaxies and thus change the kinematics for the satellites that they bring with them. In the aftermath of mergers satellites have a chance to be ejected from the galaxy by having the necessary velocity to escape a bound orbit. This processes is a contributor to the missing satellites problem (MSP). The **Missing Satellites Problem** is a phenomenon that occurs when there is a discrepancy between the theoretical number of expected galaxies and the observed amount. Understanding the Kinematic change after a merger and if satellites commonly get kicked out of orbit is imperative so that this processes can be accounted for to make more accrete future simulations.

1.3 Current Understanding

From modern simulations galactic mergers cause extended mass distributions for the final merger and an increased central density (e.g. Drakos et al. 2019b) as seen in Fig1. This extension changes the inner kinematics of the newly merged galaxy and as time progresses the kinematics will 'stabilize' and form a new system of movement for stars and new dark matter and stellar mass distributions. This change in kinematic affects gas as well, during the merger gas clouds of both galaxies can merges and create **Starburst** regions, which are areas of significant star formation (e.g. Ejdetjärn et al. 2025).

1.4 Open Questions

Although M31 and the MW are the two giants in focus, the Triangulum Galaxy (M33) is a satellite galaxy of M31 and it will be subject to the kinematics of the merger of M31 and MW. This poses the question, will M33 be bound to the galaxy for will it have the velocity to escape the pull off from the merger?. Other questions include, 'How does the assembly of a central galaxy affect the mass profile and shape of the dark matter halo?' Abadi et al. (2010), 'How do mergers effect galaxy characteristics like gas kinematics and star formation history? Ejdetjärn et al. (2025), and 'How are the structural properties of the dark matter halo related to it's growth history?' Drakos et al. (2019a).

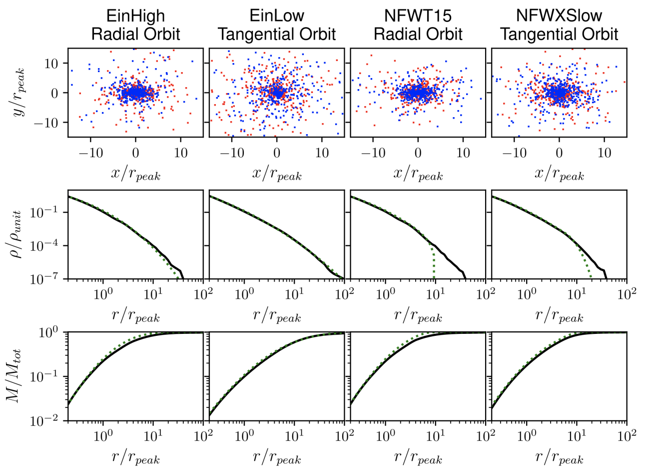

Figure 1. Results of 4 merger simulations form Drakos et al. (2019a). The bottom row of plots are the mass profiles. From the plots we can see that at as expected the final merger (solid black) has a higher density profile (ρ)

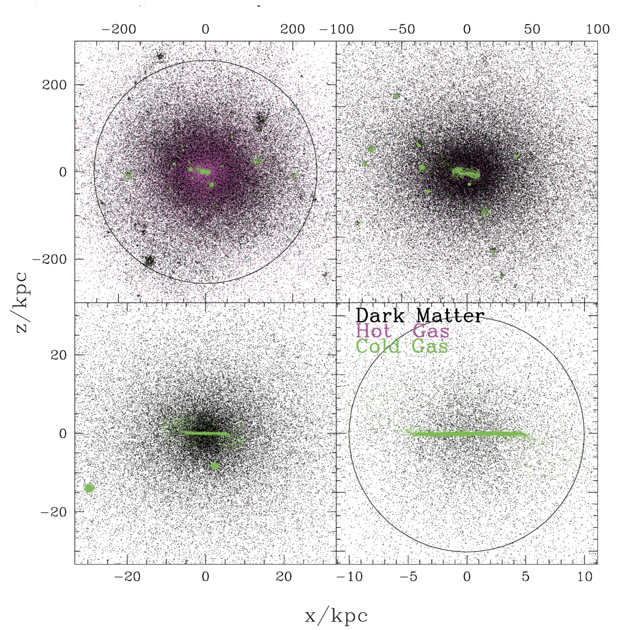

Figure 2. Distribution of simulated Dark Matter particles and gas particles in black and red/green respectfully. The distribution shows how the Dark matter in the halo is very spread out and is in no way a 'point mass'. Figure from Abadi et al. (2010)

2 THIS PROJECT

2.1 My Project

In this paper we will look at the kinematics of the merger remanent of M31 and the Milky Way to determine if the satellite galaxy M33 is bound or unbounded to the remanent. I will look to answer the questions, *What is the escape speed of the remnant as a function of radius* and *How does the escape velocity vary when computed treating the Dark Matter Halo as a point mass vs fitting a Hernquist profile and using analytic potential.*

This project tackles the open question *will M33 be bound to the galaxy for will it have the velocity to escape the pull off from the merger*? This answer to this question will shed light on the missing satellites problem and is potency in major mergers. If M33 is kicked from the galaxy after the merger then we can infer that galaxy mergers could be one explanation for the difference in expected vs observed satellites.

3 METHODOLOGY

3.1 The Approach

This project uses data files from the N-body simulations form van der Marel et al. (2012). The simulation from this paper predicts the dynamics of the bulge,disk,and halo particles of M33, M31 and the Milky Way. The data used comes from specified "snapshots" in the simulation which are files with particle position and velocity at a specified time that correlated to the "snap number". The N-body simulation is a computer program that simulated the moment and interactions of N number of particles/bodies.

By the end of this project I will have obtained two equations for the escape velocity as a function of radius. One being the well known:

$$v_{esc}(R) = \sqrt{\frac{GM}{R}} \tag{1}$$

And the other will be calculated using the potential of the at each given radius which will take the form of:

$$v_{esc}(R) = \sqrt{2|\Phi|} \tag{2}$$

The potential (Φ) will consist of three components, one from the bulge, one from the disk, and one from the Halo. The potentials from the Bulge and Disk will be calculated using EQ1 with their masses being treated as point masses, but the Halo mass will be calculated by fitting a Hernquist profile to the merged dark matter profiles of MW and M31. The Hernquist profile is designed to proximate the distribution of mass in galaxies as mentioned in Hernquist (1990). When the Hernquist profile is fitted it will give the mass (M) and scale length (a) that is needed for the potential equation:

$$\Phi(R) = \frac{-GM}{(R+a)} \tag{3}$$

The scale length will be determined by plotting the mass profile like in the 5th homework. The Halo masses of M31 and the MW will be concatenated into one array and a Hernquist profile will be overlaid until a scale radius (a) is found that best fits the halo mass. After a scale radius has been determined the potentials of the halo,disk,and bulge will be summed together and used in EQ2.

I will combine codes from previous homeworks and labs with two new codes that will be written just for this project. I will use the Homework 2,3,4,and 5 codes which are the Python scripts that read data files, sum the total mass of components, and fit a Hernquist profile respectively. I will also use code from Lab 4 for the Hernquist profile. The first new script will be a code that takes the total mass of the merged MW and M31 galaxies and plots v_{esc} vs radius and the other that plots $v_{esc,Hernquist}$ vs radius. Both codes will use all three particle types but the disk and bulge (types 2 and 3) will only be used to calculate the total mass of the disk and bulge. Type 1 particles (Halo) will be the type that has a Hernquist profile fitted to. I will use a snapshot after M31 and the MW merge and a clear remanent is determined. Snapshot 650 from the low resolution will be an ideal choice because it will be long after the merger of the two galaxies and the dark mater halo will have stabilized. Low resolution snapshots are also ideal as they contain the necessary mass values while not containing unnecessary data on individual particles. A stabilized halo is required for the study of its kinematics. The snapshot will be obtained form the simulation by (van der Marel et al. 2012) of the merger of M31 and the Milky Way. Lastly, I will determine if M33 has a sufficient enough velocity at its center of mass position to escape the merged remanent. The center of mass position and velocity will be determined using code from homework 4 with only the disk particles taken into account. The calculated position and velocity of the center of mass of M33 will will be added on to the point mass and Hernquist plots to see if it is bound or not.

3.2 Hypothesis

Before any computation we can already tell that method 2 (2) will be a more accurate conclusion than method 1 (1) since method 1 assumes all the mass is concentrated at a single point. This is an incorrect assumption as Dark matter halos can stretch out far beyond the disk and bulge as seen in Fig2. The expectation is that the plot of method one will resemble a function of the form:

$$y(x) = \frac{C}{\sqrt{x}} \tag{4}$$

Where C is some constant that will be determined during computation. Method 2 will be more accurate since it will take into consideration the change in enclosed mass as we move further out into the halo. The expectation of the plot of 1vs2 is that the slope will either not be linear or the slope will not be 1. The trend of the plotted line will show the discrepancies of the simplification approach.

For M33 we expect the satellite to remain bounded to the system. With the amount a mass that will be in this new merged galaxy the necessary velocity for escape will be astronomically high and very difficult for M33 to reach.

4 RESULTS

By plotting the Hernquist mass profile with a scale radius of $a = 85$ and comparing to the remanent halo mass as a function of radius we get the plot 3:

By using the scale radius of 85 from the mass profile plot we first assume a point-mass approximation, and we revive the plot 4. This plot has the form of a $y = \frac{1}{x^2}$ plot. The plot was made by summing the mass of the halo, disk, and bulge into one value and plugging that mass into the escape velocity equation 1. The escape velocity appears to approach zero very quickly and is very close to 0 around $r = 1 - 2$. One major observation is that the y-axis is on the scaling of 10^{11} so the plot going to $0\frac{km}{s}$ at around 2 kilo-parsecs is visually misleading.

When the Hernquist mass profile is taken into consideration, one receives the plot 5. This plot has a similar form to 4 however, the magnitude of the y-axis is smaller. The key difference here is that the mass of the halo is not taken as a pint mass and is treated as a function of radius as explained in the methodology section.

As seen in figures 6 and 7 the speed of M33 is below the necessary velocity to escape the remanent.

5 DISCUSSION

From plots 4 and 5 we can see that the point mass escape velocity, v_{point} is larger then the Hernquist escape velocity v_{Hern} along the entirety of the radial distance outwards. By taking the apparent maximum velocities from the plots we see:

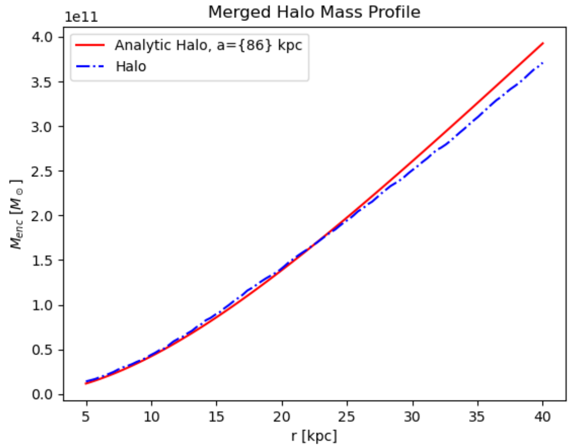

Figure 3. The x and y axis are radius away from the galactic COM and the mass enclosed respectively. The dashed line is the Halo mass from snapshot 650 and the solid red line is the estimated Hernquist halo mass profile. The chosen scale radius to represent the merged remanent was 86 kpc.

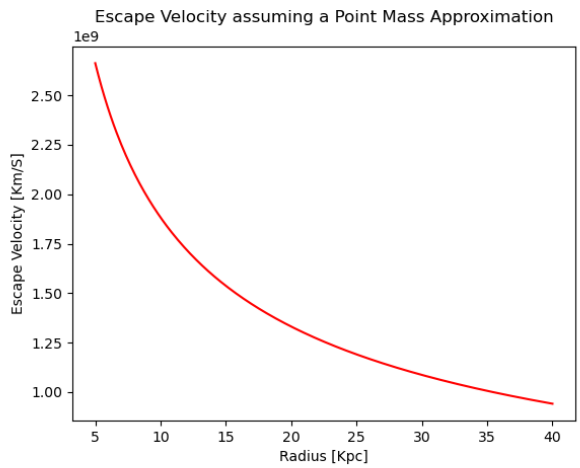

Figure 4. The x and y axis are radius away from the galactic COM and the escape speed as a function of distance respectively. As we can see the highest achievable escape speed is achieved very close to the COM and is around $v_{esc} \approx 2.75 * 10^9 \frac{km}{s}$.

$$\frac{v_{point}}{v_{hern}} = \frac{2.75 * 10^9}{6.5 * 10^8} \approx 4.23 \tag{5}$$

From this we can infer that on average the point mass approximation velocities are around 4.23 times as larger then that of the Hernquist velocity. This means that in the point mass approximation it is much harder for something to escape the galaxy remanent. The hypothesis was that both plots would take the shape of a $1/x^2$ plot which is exactly what we see from 4 and 5 so this result does agree with our hypothesis.

From figures 6 and 7 we see that the velocity of M33 is lower than the escape velocity of the remanent. This means that M33 remains bounded to the system from around 132 kpc away. This result is

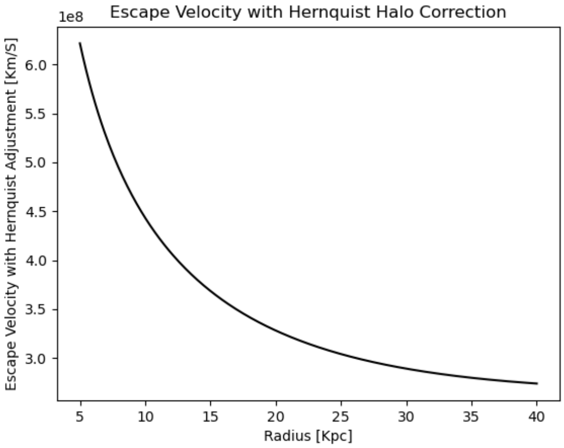

Figure 5. The x and y axis are radius away from the galactic COM and the escape speed as a function of distance respectively. As we can see the highest achievable escape speed is achieved very close to the COM and is around $v_{esc} \approx 6.5 * 10^8 \frac{km}{s}$.

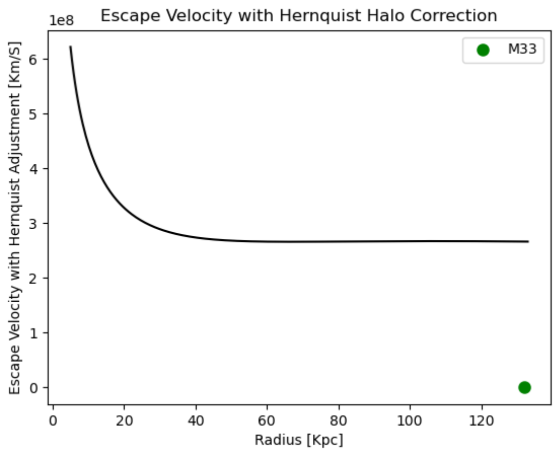

Figure 6. The x and y axis are radius away from the galactic COM and the escape speed as a function of distance respectively. The green dot represents the speed and position out of the satellite galaxy M33. As we can see the speed of M33 is well below the escape velocity of the Hernquist halo mass approximation.

exactly what was expected from the hypothesis. Since M33 remains bounded to the system, M33 will not contribute to the missing satellites problem. It was expected that M33 would remain bounded due to is high mass and large size, and while M33 does not contribute to the MSP, we do not know if other satellites, like the small and large Magellanic clouds will remain bounded or not. An important thing to remember is that this conclusion was derived from simulation data and the method to determine this treated the disk and bulge of the milky way and M31 as point masses. This method make the code development easier but likely make the resulting escape velocities higher then they would be when r is close to the remnants center of mass. However, since M33 is so far away from the COM ($r \approx 135$) the conclusion of M31 remaining bound is not affected.

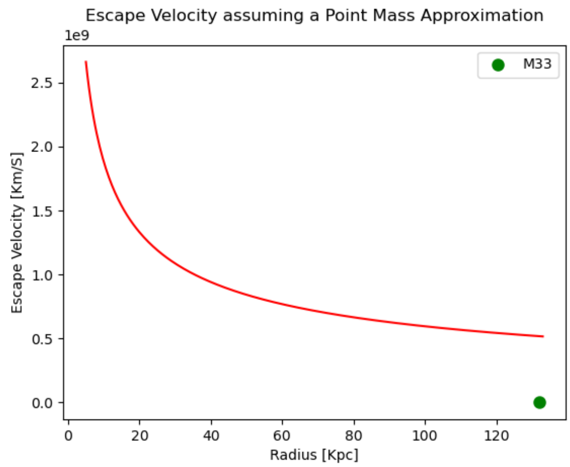

Figure 7. The x and y axis are radius away from the galactic COM and the escape speed as a function of distance respectively. The green dot represents the speed and position out of the satellite galaxy M33. As we can see the speed of M33 is well below the escape velocity of the point mass approximation.

6 CONCLUSION

The Kinematics of a galaxy is crucial to defining it and understanding how it works, among many characteristics the escape velocity of a galaxy is very important as set the speed limit that an object can have before it becomes unbounded to the galaxy.

We found that M33 is expected to remain bounded to the merged remanent. The biggest gain is that M33 will not contribute to a missing satellite problem for the merged Milky way and Andromeda galaxy. While we do not have data about other satellites like the LMC and SMC, from what we do have we can say that there is no missing satellite problem in this simulation.

Further improvements would include including simulation data for the LMC and SMC. These satellites are bound to the Milky Way and are the two most well known, so testing to see if they are bound or unbound for the future would be a good addition. While the point mass solution have an expected result, the Hernquist approximation could be improved. The two main ways would be by finding a better way to approximate the disk mass distribution. In the code the bulge and disk masses were treated as point masses. To get a more accurate escape speed at low radii a proper disk mass distribution approximation should be added to the code.

7 ACKNOWLEDGMENTS

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This project used the software of Python Van Rossum & Drake (2009), Numpy Harris et al. (2020), and Matplotlib Hunter (2007) to create the plots shown and to calculate all values needed.

The papers cited and referenced throughout this paper were found using NASA ADS Wagg & Broekgaarden (2024).

We respectfully acknowledge the University of Arizona is on the land and territories of In-digenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. The University strives to build sustainable relation-ships with sovereign Native Nations and Indigenous communities through education offerings,partnerships, and community service.

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