Weber Research Assignment 6

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1 INTRODUCTION

Dark matter halos are believed to be located around galaxies, extending much further than the visible length of their galaxy. A dark matter halo is a large cloud of dark matter that engulfs the visible matter in a galaxy. The length of the halo is typically much larger than the visible length of the galaxy. Since a dark matter halo has a gravitational force, it stands to reason that the dark matter halo of a **satellite galaxy** would change in shape drastically due to a nearby **major collision**. A satellite galaxy is a galaxy that is gravitationally bound by a larger galaxy. A major collision is a collision between two galaxies of similar mass.

The evolution of the **halo shape** of satellite galaxies during a nearby major merger is very important to understanding how dark matter and visible matter interact gravitationally. The halo shape is the shape of the dark matter halo. This can include where dense regions reside, how stretched out it is, its overall ellipticity, its radius, and its general shape around the rotational axis of the galaxy. The shape around the rotational axis is either **prolate**, **oblate**, or **triaxial**. An oblate shape is a spheroid that is stretched out to resemble the shape of a disk, a prolate shape is a spheroid that is stretched out to resemble the shape of a football, and a triaxial shape is a combination of an oblate and a prolate shape. With the information provided by understanding the shape of the halo, we can better understand **galaxy evolution** by being able to predict how the gravitational pull of the dark matter halo can reshape the galaxy. Galaxy evolution is how **galaxies** throughout the universe form, merge, and evolve over time. A galaxy is a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons and newtons laws of gravity. The halo shape can also increase our knowledge of galaxy evolution by allowing us to more accurately determine the gravitational pull of galaxies on one another during a galactic merger. Since so much of a galaxies mass is part of the dark matter halo, it would be nearly impossible to predict how galaxies interact gravitationally without it.

At this point, we know for sure that dark matter has a gravitational pull on the mass around it. Otherwise, galaxies wouldn't have enough of a gravitational force to hold themselves together. Dark matter accounts for roughly 85 percent of the mass in the universe. Since dark matter accounts for most of the mass in any given galaxy, it is really important to understanding how galaxies evolve as they collide. We have also observed evidence of dark matter interacting differently than light during galaxy collisions (Clowe et al. (2006)). We know that dark matter is distributed in clumps (Banik et al. (2018)). We know that the gravitational pull of a galaxies dark matter halo can affect the shape of visible objects within a galaxy like stellar clusters (Erkal et al. (2017)). The dark matter halo also provides a medium

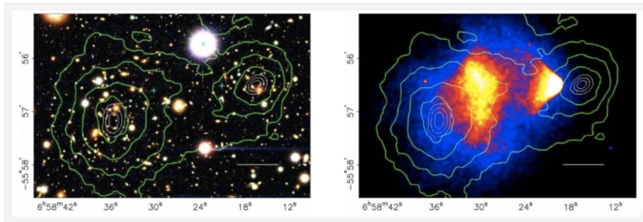

Figure 1. on the left is a contour diagram of the mass distribution of the galaxy measured using gravitational lensing. On the right is an x-ray of the same galaxy. Not only does this serve as a way to map it, but it also confirms that the dark matter behaves differently than the visible mass of the galaxy due to a galaxy collision.

to slow down galaxies when they pass through each other by causing an energy loss, allowing for them to merge instead of just passing through each other. As shown in **figure 1**, we also know that the dark matter halo of a galaxy can behave differently than the visible matter during a galaxy merger.

Many of the primary questions relating to dark matter relate to its distribution. Depending on different models, dark matter is believed to be distributed in either many smaller clumps or fewer large clumps. Dark matter could also be distributed in several different ways around the rotational axis of the galaxy. The dark matter halo around galaxies could be either a prolate, oblate, or triaxial halo. It has been theorized that dark matter clumps could exist as galaxies of their own. Dark matter galaxies could explain the irregular shapes of some galaxies. This could be what is causing the irregular shape of a stellar cluster orbiting around the Milky Way (Erkal et al. (2017)). While we know that it can be affected differently than visible mass during a galaxy merger, we don't know why the dark matter halo can behave differently. Another big unknown relating to dark matter is how it can be transferred from one galaxy to another. We are not sure how the **Jacobi radius** for the dark matter halo of a satellite galaxy matches what we would expect from an analytical solution of the Jacobi radius equation. The Jacobi radius is the maximum distance a gravitationally object can go until it is stolen by the gravitational pull of another object. How the Jacobi radius evolves as a third body is introduced into the system is also something that remains a mystery. Our inability to directly observe dark matter makes it difficult to attempt to answer these questions. Because we can't directly observe the dark matter halo around each galaxy, we need to observe how the visible matter enclosed within the halo evolves in ways that can't be explained without the existence of dark matter. We can use this to help determine the shape required for the dark matter to influence the visible matter in the way that it does. Since dark matter has a strong gravitational pull, we can also observe the gravitational lensing caused by the galaxy to help determine the shape of the halo.

2 PROPOSAL

2.1 This Proposal

I am aiming to analyze the shape of the dark matter halo around the Triangulum galaxy (M33) at several key points during the merger of the Milky Way and Andromeda (M31) galaxies to see how it evolves over time. M33 is a satellite galaxy of the Milky Way, meaning that it will be greatly affected by the merger between M31 and the Milky Way. The main focuses that I am going to be analyzing are the shape around its orbital axis (oblate, prolate, triaxial), how the halo appears to change in physical shape, and how the Jacobi radius of the Triangulum galaxy evolves as the merger progresses and M33 reaches its closest and furthest points from the merger.

This project aims to address the shape of the halo about its orbital axis. It also aims to address how the analytical Jacobi radius compares to the simulated radius and how both of them evolve over time as the distances of the Milky Way, M31, and M33 change during the merger.

This project will help us understand how the mass of galaxies evolves over time. It also helps us understand how a dark matter halo behaves when the nearby mass suddenly increases by a large amount. It will help us understand the behavior of the halo as it reaches its pericenter and apocenter. The shape of the halo could have large effects on the gravitational pull between M33 and the merged Milky Way and M31 galaxy.

3 METHODOLOGY

The simulations being used are the ones that were used in ((Roeland P. van der Marel & Guhathakurta (2012))). Here an **N-body** simulation of the Milky Way, M31, and M33 system was modeled. An N-body simulation is a simulation of how 3 or more gravitationally bound objects with initial masses and velocities evolve with time.

I am going to be using the dark matter particles from the M33 galaxy in the simulation data. At this point I believe that it will be best to use the HighRes simulation data to get the most accurate data possible. I am planning on using several different snapshots. I am planning on looking at the 000, 300, 340, 380, 705, and 740 snapshots. Snap 000 is the start of the simulation, so it is very important to understand its shape in order to see how it evolves over time. Snaps 300, 340, and 380 were chosen because of how close they are in time to the galaxy merger. Snap 300 is a point where M31 is at pericenter. In snap 380, M33 is at apocenter. point 340 was chosen because it is a point in between them. Snap 705 is an apocenter snap and snap 740 was a pericenter snap. These were chosen because they take place a significant amount of time after the merger.

The first thing my code will compute is the distance between the M31 and M33 galaxies and identifying the apocenters, pericenters, and midpoints of the distances between M31 and M33. My code will also compute the rotational axes that the dark matter halo rotates around, then it will redefine each particle in terms of this new coordinate system. My code will be computing how the mass enclosed within a cylinder along each axis changes as the radius of the cylinder increases. The Jacobi radius can be calculated using the equation $r_j = d(M_1/2M_{tot})^{1/3}$. (Szebehely 1967) where r_j represents the Jacobi radius, d represents the distance between the host and satellite galaxies, M_1 is the mass of the satellite galaxy, and M_{tot} is the total mass of the host galaxy enclosed within a radius d

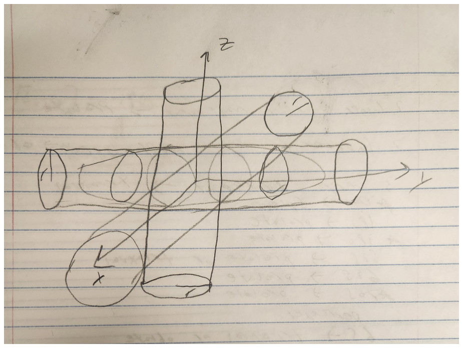

Figure 2. Two cylinders of equal radius, r, and a length of infinity surround a prolate shape. The cylinder along the y axis clearly contains more of the object than the cylinders along the x and z axes. By using this, we can determine if the shape is prolate, oblate(two cylinders contain more mass in r than the third), or triaxial (differing masses for each cylinder)

To analyze whether or not the galaxy is oblate, prolate, or triaxial, I am planning to run a function that computes the total mass enclosed within a cylinder along each of the 3 major axes. As presented in **figure 2**, In theory, the graph of mass enclosed for the cylinder will reach a certain threshold of total mass enclosed in one direction much more quickly than the other two if it is prolate. If two cylinders reach the threshold much more quickly than the third direction, it is likely oblate. If they all reach the threshold in very different radii, then it is likely triaxial. To measure the Jacobi radius, I will be making a mass density profile of M33 and plotting the analytical solution of the Jacobi radius over it. Finally, I will also be creating contour diagrams that are both face on and edge on for the dark matter halo of M33 at each of the snapshots that I am going to be using. This lets me see how the halo changes in shape as the merger goes on. Specifically, this will tell me if the halo appears to be stretched out as the simulation goes on.

I believe that the halo should be prolate, and that the Jacobi radius will vary wildly at different points of the simulation. I expect the halo to be prolate due to the gravitational pull of M31 and the Milky Way on M33. I believe that this will cause the halo to become elongated in a way that points towards the center of mass of the Milky Way galaxy and M31 galaxy. The Jacobi radius should change drastically as the simulation progresses. As seen in the equation of the Jacobi radius, it depends primarily on the mass and distance of the objects. The distance between M33 and M31 oscillates throughout the simulation, meaning that the Jacobi radius will change with it. During the simulation, M31 merges with the Milky Way, meaning that the total mass of the galaxy that M33 is orbiting around is very different by the end of the simulation. This should cause the Jacobi radius to be much smaller at the end of the simulation than the beginning of the simulation, assuming a similar distance between M31 and M33 at both time snaps. Since M33 is suddenly going to be around considerably more mass due to the merger between M33 and the Milky Way, I expect to see the halo be more stretched out in the direction facing M31.

4 RESULTS

Figure 3 is a graph of the amount of mass obtained within a cylinder along each axis as its radius expands to the Jacobi Radius at that snapshot. This is the technique demonstrated in **figure 2**. The specific

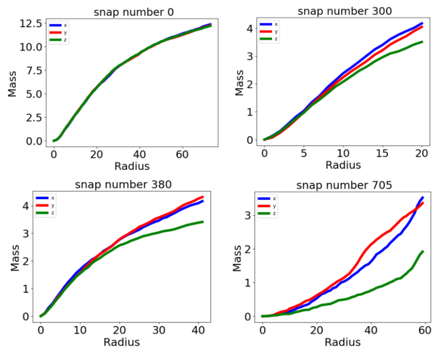

Figure 3. Contains the mass density functions for 3 cylinders, 1 along the x axis(blue), y axis(red), and z axis(green). The snaps being looked at are 000, 300, 380, and 705. This represents the mass enclosed within the cylinders as a function of their radius. The range of the radius is from zero to the Jacobi radius. Through these four snaps we can see that the shape of the spheroid appears to evolve from being something close to a sphere at the start of the simulation to an oblate spheroid as the merger takes place.

snapshots that are being looked at are 000,300,380, and 705. As you can see, the galaxy initially starts out being spherical, with all 3 mass density lines appearing to be identical. However, that is not the case in the other three graphs, where we see significantly more mass enclosed within the cylinders along the x and y axes than the cylinder along the z axis at the Jacobi radius. This leads to the conclusion that the dark matter halo transformers into an oblate spheroid as a result of the galactic merger.

Figure 4 contains 2 graphs. One graph shows the average halo particle distance from the center of mass as a function of time throughout the merger. The other contains the average distance in the x, y, and z directions from the center of mass as a function of time. Through this graph we see that the average distances of particles in the x and y directions are roughly two times that of the average distance in the z direction. This information actually supports our data from **figure 3**, if the mass along the z axis is clustered, we could expect the cylinders along the x and y axes to contain much more of that mass. Through this graph we are also able to see that the mass of M33 is getting stretched out as time expands.

Figure 5 takes the values under the graphs from **figure 1**, but for several more snapshots, and graphs them as percentage values out of the total mass enclosed in any cylinder at that snaps analytical Jacobi radius. This is graphed as a function of time in Gyr. The primary reason for turning the values into percentages is to prevent the stretching of the galaxy from making it harder to analyze the evolution of the shape within the Jacobi radius. It's much easier to compare the axes to one another at different snaps when the three lines being graphed always add up to one for each snapshot. We can now see the evolution of the shape of M33 at the analytical Jacobi radius throughout the whole simulation. At the time of the merger, it is clear that the average z distance is much smaller than the average x and y distances. However, as we enter into the higher snaps, we can see that the average distance of a particle in the y direction is clearly larger than the average distance in the x direction. Since we find that the x, y, and z axis cylinders all look quite different in the later time snaps, this leads to the conclusion that M33 actually goes from being spherical before the merger, to oblate around the time of the merger, and then to triaxial at a period far after the merger.

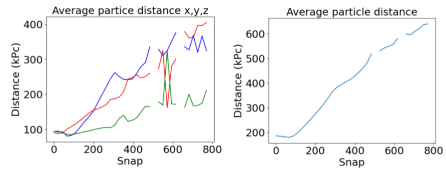

Figure 4. The first graph contains the average distance of a particle from the center of mass in Kpc as a function of time. The second graph looks at the average distance from the center of mass in the x (blue), y (red), and z (green) directions in Kpc as a function of time in Gyr. Through this we can see that the halo particles seem to be more stretched out along the x and y axes than the z axis. We can also see that the dark matter halo is expanding as time goes on.

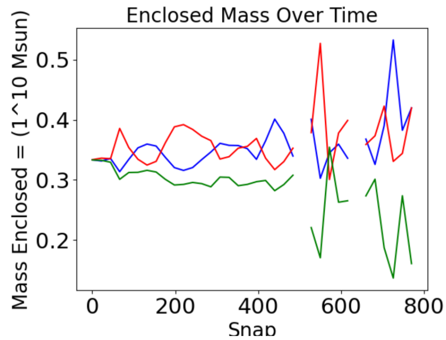

Figure 5. This takes the mass enclosed in the cylinders from **figure 3** at the Jacobi radius specifically (the final value in the graphs from **figure 3**), normalizes them to make them percentage values for each snapshot, and graphs them as a function of time in Gyr. This allows us to analyze the shape of M33 at the Jacobi radius at several different snaps. Through this, we can actually see that there is much more mass enclosed along the y axis cylinder (red) than the x axis cylinder (blue) at the higher snaps. The z axis cylinder (green) still consistently contains less mass than the x and y cylinders. This shows us that the M33 halo is actually triaxial at points far after the merger.

5 DISCUSSION

Result 1: As time goes on, the shape of M33 at its analytical Jacobi radius evolves from its initial spherical shape, to an oblate spheroid around the time of the merger, to a triaxial spheroid far after the merger. This completely defies my hypothesis. I assumed that some of the edge particles of M33 would be stolen by M31, causing the shape to have a more prolate shape. It is clear that this is not the case. The stretching of the mass within M33 along its xy plane caused the average particle radius along the z axis to shrink creating an oblate spheroid, as opposed to a prolate spheroid. I also believe that the angular momentum of the galaxy could make it much easier to stretch out the halo. My hypothesis also was working under the assumption that M31 would lie somewhere along the xy plane, which it very likely doesn't (in hindsight, there was no reason for me to make this assumption to begin with). I believe that the y axis being more stretched out than the x axis has to do with the distance vector between the two galaxies' centers of mass potentially being more aligned with the y axis than the x axis. This reduces the stretching of average x location of a halo particle while also stretching the average y location out by pulling on it gravitationally.

Since dark matter makes up most of the mass of the galaxy, and is not necessarily evenly distributed throughout a galaxy, it can be really difficult to predict how the dark matter will stretch as the merger happens. This can help us model the shape of the dark matter halo using how much it stretched out to infer the total mass and density of the halo at the first snap in the simulation. The change in shape of the halo means that we can also assume that it pulls on the visible matter with different strengths throughout the simulation. We can use this to help support the theory that dark matter is causing the irregular shapes of some of the stellar streams located around the milky way (Banik et al. (2018)). More of the matter within the halo being closer to the xy plane would lead to it having a stronger gravitational effect on the visible matter within the disk. The halo doesn't always evolve with its galaxy as a result of a collision (Clowe et al. (2006)).

Most of the uncertainties stem from the fact that I am just looking at the relationship between M33 and M31 during this merger. At this point, none of my calculations account for the fact that the Milky Way should also have large effects on the calculated Jacobi Radius between M33 and the Andromeda galaxy. While I do believe that the cylinders are providing me with accurate data, the lack of any sort of limitation on the cylinder height could be causing me to look at particles that have been launched outside of the galaxy. Measuring the Jacobi radius and using that radius for every cylinder could also be quite limiting, since the Jacobi radius is only relevant in the direction pointing from the center of mass of M33 towards the center of mass of M31. a particle can be outside of the Jacobi radius and not be at immediate risk of being stolen if it is on an opposite side of the galaxy as M31 is.

Result 2: The radius of the dark matter halo seems to be expanding as time goes on. This satisfies my hypothesis that the shape of the galaxy would be more stretched out towards the direction of the Milky Way. However, it seems to be more stretched out in every direction. This is likely explained by the rotation of M33. As particles that are closest to M31 get pulled towards it, they rotate around M31, leading to a new set of particles that are closest to M31 and getting pulled on the most. This causes M31 to be stretched out in all directions over larger periods of time

Through this result, we see that dark matter interacts with itself gravitationally in the same way that we have observed visible matter interacting with itself. We would expect a halo of visible matter in M33 to be stretched out in the same way as the dark matter halo was. If we are allowed to assume that dark matter behaves the same as other particle types in a galactic merger, this could help us model far more accurate dark matter halo shapes. The dark matter halo being stretched out would also lead to it pulling some of the mass of M33 out with it. This would increase the stretching of the galaxy. Being able to analyze how the galaxy becomes more stretched out over time could give us a great understanding of how much dark matter is surrounding each galaxy. At some point, this increase in average particle distance could lead to the galaxy being ripped apart, creating stellar streams around the Milky Way (Banik et al. (2018)).

While we can clearly see that the average halo particle distance from the center of mass is increasing, the graph may not accurately represent by how much. What the graph is failing to account for is that some of those particles have been stolen by M31, and are now in orbit around its center of mass, as opposed to the center of mass of M33. This means that we could be graphing some particles that are no longer a part of M33.

REFERENCES

Banik N., Bertone G., Bovy J. Bozorgnia N., 2018, JCAP, pp 1–2

Clowe D., Bradac M., Gonzalez A. H., Markevitch M., Randall S. W., Jones C., Zaritsky D., 2006, ApJ, pp 1–2

Erkal D., Koposov S. E., Belokurov V., 2017, pp 1–2

Roeland P. van der Marel Mark Fardal G. B. R. L. B. S. T. S. J. A. T. B., Guhathakurta P., 2012, The Astrophysical Journal