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NICOLE ZAWADZKI 400B RESEARCH PROJECT

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ABSTRACT

Throughout the merging of the Milky Way and M31, material from M33 will be removed through tidal stripping. Discovering how this changes the internal structure of the stars in the satellite can lead to further insights into the formation of Dwarf Spheroidal Galaxies. In the report I examine the evolution of the density profile, and look for evidence of tidal truncation. This allows us to understand where material is stripped from M33 and what percentage remain bound to the satellite. I found that the tidal radius closely mirrors the orbit of M33 around the MW/M31 system. The inner regions of M33 become less dense, with stellar particles extending out as far as 500 kpc from M33's center of mass.

1. INTRODUCTION

During the merging of the Milky Way and M31 it is possible for material to be stripped from M33 through the process of tidal stripping. Tidal stripping is due the gravitational potential of one object removing material from a less massive object. This material can be gas, dark matter, or even stars. Since this is a differential potential, streams of material are created in front of and behind the smaller object. Leading tidal streams form in the direction of the massive host and tailing streams form away from the host galaxy. The tidal radius, or break radius, of an object is the distance from its center of mass where the tidal force from the larger object overcomes the self gravity of the less massive object. (van den Bosch, et al. 2018) In the context of this project, there is a chance M31 will tidally strip material from M33, and the radius at which this happens from M33's center of mass is its tidal radius. Particles in M33 at or beyond this radius will become unbound and contribute to the leading or trailing tidal streams. Through simulations done by Lokas et al. 2015, they showed that tidal forces are strongest when the satellite is in a prograde orientation, 0°inclination, to the host galaxy. Considering M33 is oriented 43°"below" M31, (Corbelli & Schneider 1997) investigating the extent of tidal affects on the satellite could yield interesting results. It is logical to think that the tidal force will being stripping material from the outskirts of the galaxy, but the specifics are still not fully known. It is also not clear if removing material from the outskirts of the system will change the dynamics and structure of the other particles. It is thought that tidal effects of galaxy mergers lead to the formation of dwarf spheroidal galaxies(Łokas, et al. 2015). M33 is interesting in itself because it is about the same mass as the LMC, a dwarf galaxy around the Milky Way, but has a higher rotation curve. It will be interesting to see if it behaves like we expect dwarf galaxies to.

2. PROJECT

For this project I explored how the density profile of M33's stellar particles evolves throughout the simulation. Depending on how the profile changes, it can indicate areas of the galaxy that are more or less dense than before the merger. Finding any changes means that the stellar particles are being moved into or away from the center. Both scenarios can imply that the the tidal forces caused by MW and M31 are changing the distribution of stars in M33's disk. The density profile can be used to find the tidal radius of M33 by looking for where the slope of the profile at larger radii changes. This is an indication of the beginning of a tidal stream. Depending on how great the difference is between these properties before, during, and after the merger will determine how effective the tidal forces were at stripping and changing the structure of the stars in M33's disk.

3. METHODS

This section goes through the code used to analyze and answer the questions addressed in the section above.

3.1. *Simulation Data*

All of the data used during this investigation was created through a simulation done by van der Marel, Besla 2012. Their paper reports the results of the collisionless N-body simulation and semi-analytic orbit integrator. The N-body simulation used initial conditions constrained by observations and by current literature. The simulation included dark matter, disk, and bulge particles for all three galaxies, with the exception of M33 which was assumed to be bulgeless. Gas particles were also not included because other simulations that did include the gas found that the induced features match normal spiral merger simulation, so it was not of major consequence to discount the gas. (van der Marel, et al. 2012) The halo masses for all three galaxies were modeled using Hernquist profiles. The black hole in the center of each galaxy was included, not merely for its mass, but because it closely followed the center of mass for each galaxy. The simulation began at the current epoch and was designed to reflect current conditions. The simulation ran with the Milky Way at the origin of the Galactocenter frame. It then ran through the merger outputting the time in giga years, the type of particle, mass of the particle, 3D position, and 3D velocity. This output of data happened around every 14 mega years. The text files associated with each output are labeled with the galaxy's name, and which number data dump it was.

3.2. *Density Profile*

The first step in this project was to decide which snapshots were best to use. Using all 800 would be too time consuming and tedious. On the other hand, the internal structure of the stars could change frequently, so only looking at one shot before, during, and after the merger wasn't sufficient. To solve this problem I wrote a code that found the time of each apocenter and pericenter of M33's orbit around M31 and then found the snapshot associated with that time. This was achieved by using sections of code written for Homework 6. For that assignment I created a function that read in the information from each snapshot and stored the stellar particle data into a text file for each galaxy. I edited that code to also include the snapshot in the text file. This is done in the Snaps notebook. By reading in those text files, finding the separation between M33 and M31 at each snapshot, I identified any time where there is a maximum or minimum. This indicated an apocenter or pericenter in the orbit. I then went through the M33 orbit text file and found the snapshot that occured at those times.

I then created a function that found the density within a radius shell. It found the total mass of stellar particles within two radii and divided by the volume of that shell to get the density. The volume of a spherical shell is $(4/3)\pi(R^3 - r^3)$ where R is the outer radius and r is the inner radius of the shell. I went through this process for each snapshot and plotted them all together. The goal was to look for where the slope at the end of the density curve diverged. It has been shown that this is an indication of the break radius. (Łokas, et al. 2015) The slope breaks and becomes less steep because material is being pulled from the outskirts and there continues to be material further out from the center, as opposed to dropping off at the edge of the galaxy.

Another way of thinking about the density of M33 is through a histogram. By plotting the number of stars within a range of radii, the density of that area can be inferred. This was a good way of investigating the changing density in the inner regions. The second part of the Density Profile notebook used a function that found the number of particles within a shell of radii. It then plotted the number of stellar particles within that shell at each snapshot. The tidal radius could also be seen through this method. Again, rather than the number of particles suddenly dropping off, there was an extended tail of a small number of particles out to large radii.

3.3. *Analytic Tidal Radius*

It was useful to compare the tidal radius seen by eye within the density profile and histogram, to the analytic calculation of the tidal radius. This calculation was dependent on the masses of both galaxies, and their distance from each other. $TidalRadius = R(m/2M)^{1/3}$ where m is the mass of the object begin stripped, M is the mass of the larger object, and R is the distance between the two (van den Bosch, et al. 2018). This worked for a two body problem, but there were times when MW was close enough to M33 that it was possible that the Milky Way's potential contributed to the stripping of M33. To account for this, a caveat was added to the code. When MW and M31 center of masses were within 20 kpc of each other, M went from being the mass of M31 to the combined mass of MW and M31. 20 kpc was chosen because both MW and M31's disks are between 15-25 kpc. This was important for a couple reasons. One, being that close their disks and dark matter halos would be mixing and both interacting with M33's. Also, their black holes would be close enough that finding M33's average distance from MW and M31 would be sufficient for the tidal radius calculation. The calculation was done as a progression, first assuming all three galaxies were point masses, then adapting a Hernquist profile for each, and lastly assuming M33 was a point mass and M31 and MW had extended profiles as a check of understanding. For the Hernquist profiles a new scale length was not calculated at each snapshot because it was assumed that the dark matter density profiles did not change dramatically. See Jenny Calahan's report for details on M33's profile evolution.

4. RESULTS

Using the data from the orbit text files described in the beginning of the methods section, the tidal radius was calculated over the orbit of M33 and plotted over time. The similarity between the physical distance between M33 and M31, and the changing tidal radius is apparent in Figure 1. The tidal radius of M33 mirrored

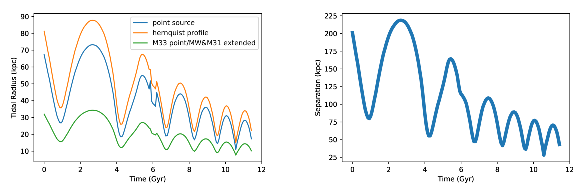


Figure 1. : a.The tidal radius of M33 was calculated along its orbit around M31 assuming all three galaxies were point masses, all three had extended Hernquist profiles, and that only M33 was a point mass. b. The physical orbit of M33 around M31 for comparison.

its orbit, and the closer it got to M31 or the Milky Way the shorter the tidal radius became. The tidal radius was shorter at the pericenter because, being closer to M31 or the merged MW/M31 system, their potentials were pulling on M33 more strongly and stripping material further into the satellite. That is, the distance from the center of M33 at which stars become unbound because of the larger galaxies' potentials was smaller when M33 was closer, than when it was further away.

The density profiles of each snapshot can be seen in Figure 2. This was achieved by using the density profile function on all of the desired snapshots and plotting them onto the same grid. Doing this made it easier to compare the different snapshots. Based on this plot is can be seen that the density in the outer regions of M33 changed during the merger. The inner regions seen uniform, and then at around 2 kpc the profiles diverge from each other. The variation in the different profiles at these larger radii can be attributed to the tidal forces pulling material from the outskirts of M33 further from the center. This plot demonstrates the idea that the profile is changing, but it is difficult to see a clear change in slope, or break radius, so this idea is further explored in Figure 3. The density profile for 2 snapshots are plotted along

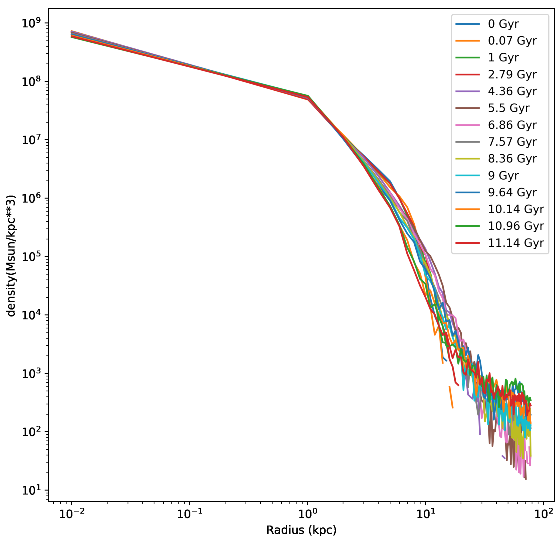


Figure 2. : Density of stellar particles at different radii. Plotted for relevant snapshots throughout simulation.

with a line indicating where the calculated tidal radius was located. These were snapshots of the first apocenter and second pericenter after MW and M31 merge. The

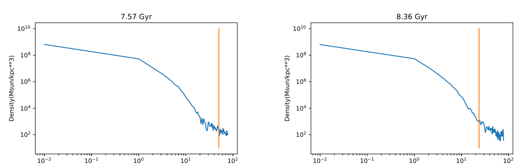
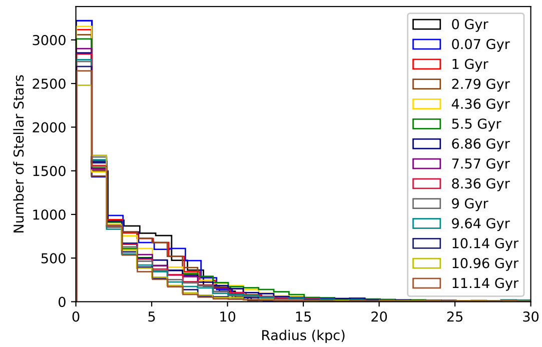


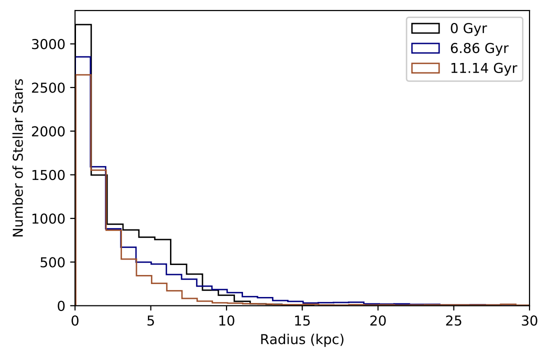
Figure 3. : a.Density profile of the first apocenter after the merger in blue and the calculated tidal radius in orange. b.Density profile of the second pericenter after the merger in blue and its calculate tidal radius in orange.

calculated tidal radius and the break radius in the density profile at 8.36 Gyr matches. The reason the two don't match as well at 7.57 Gyr is because this was at an apocenter of M33's orbit once a tidal stream had already formed. Stellar particles had already been stripped from the satellite during a past close approach to M31. So, even though the tidal radius at 7.57 Gyr was at around 50 kpc, material closer to the center of mass had already been stripped and the evidence of this remained in the density profile. This was also confirmed in Figure 5 by looking at where the calculated tidal radius lied on the histogram for these snapshots.

Doing a histogram of the number of particles within a bin of radii turned out to be useful for seeing the changes to the density of the inner regions of M33 and as a second check for the calculated tidal radius. The bin size of each histogram was adjusted to account for the large radii some of the particles went out to. The bin size of each histogram was effectively the farthest radius a particle went to. This means that the width of every bin in every histogram was around 1 kpc. In Figure 4 the x-axis was cut off at 30 kpc in order to better see the inner area



(a) Histogram of the number of particles within a radius at each snapshot.



(b) Histogram of the number of particles within a radius for the first snapshot, right after the merger, and one of the last snapshots

Figure 4. : Looking at the number of particles within 1 kpc bins. This is another way of looking at the distribution of stellar particles in M33.

of M33 better. Once the tidal streams are formed, they extended out beyond 500 kpc. Including the extended histogram made distinguishing the interesting features of the inner region of the satellite difficult. Looking at the lower plot in Figure 4 it can be seen that the overall number of stellar particles decreased in each bin with each snapshot.

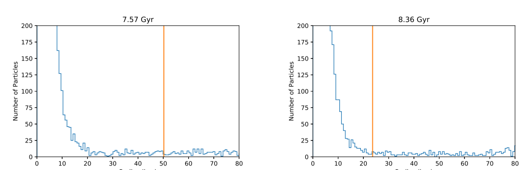


Figure 5. : These are histograms of the number of particles within a radius in blue and the associated calculated tidal radius in orange. Like Figure 3 the left histogram is of the first apocenter after the merger and the right is the second pericenter. This is a "zoomed in" graph, cutting the y-axis off at 200 particles and the x-axis off at 80 kpc in order to better see the beginning of the tidal stream.

5. DISCUSSION

Through this analysis I learned that tidal streams do form because of the potentials of M31 and the Milky Way. The distance at which material was stripped from M33 was dependent on how far the satellite was from the larger galaxies. This implied, and was shown, that this distance, the tidal radius, mirrored the orbit of M33 around the MW/M31 merger. I also confirmed that the tidal forces were stronger when M33 is closer to the more massive galaxies because the tidal radius was smaller, or closer to its center of mass. The density profiles showed that M33 becomes less dense over time at larger distances, and the histograms showed that this was also the case in the inner regions. This can mean that as material is pulled from the outskirt of the satellite, material in the inner regions move outwards as well.

6. CONCLUSIONS

As M33 orbits around M31, the gravitational potential of the more massive galaxy strips material from M33 in a process called tidal stripping. The effect of this force changes continuously throughout the simulation. The closer the bodies are, the greater the effect. The most tidal stripping occurs at the pericenters of M33's orbit. Based on the histograms and density profiles, M33 becomes less dense over time. This could lead to it becoming a Dwarf Spheroidal galaxy, but more investigating will have to be done into M33's rotation curve, and velocity dispersion after the merger. Material is pulled first from very edges of M33, and as the stripping persists, the effect happens further inward toward the center of the satellite.

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