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GRAVITATIONAL WAKE OF M33 IN THE DARK MATTER HALO OF M31 AND THE MILKY WAY

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ABSTRACT

In this project, we investigated the effects of the dark matter halo of M31 and the Milky Way on the satellite galaxy, M33. We primarily employ code to analyze the population density of dark matter particles surrounding a localized area defined by the center of mass of M33. The investigation of wakes is critical for understanding aspects of the morphology of galactic evolution. We seek to find out if the wake is visible. Upon finding the wake, a new vein of analysis becomes available, for example halo resonances or warping of the disk in spiral galaxies. Our analysis did not provide a clear and distinctive wake. We can take this result to mean that our analysis needs further rigor and more thoroughness in order to sift out the necessary particles to definitively show the wake of M33.

Keywords: galaxies: halo, dark matter, satellites, simulation galaxies: individual(M33, Milky Way, M31)

1. INTRODUCTION

A continuing problem in today's galactic field is the investigation of gravitational wake experienced by small dynamical bodies. The gravitational wake, in general, is product of two dynamical bodies interacting and passing through each other. The forces of dynamical friction (DF), first presented by (Chandrasekhar 1943), act to slow the trajectory of these two bodies. In the context of one large body and a comparatively small one, the smaller one feels a significantly larger drag force and tends to follow an orbit that spirals inwards.

It is of particular interest to be able to analyze and model the wake of small dynamical bodies through significantly larger bodies so that we can have a better understanding of how they interact. With this knowledge, we can better predict the morphology of our own galaxy and also understand how other galaxies got their current shape with an emphasis on how satellites particularly can shape the halo, disk, and bulge.

We inquire about this topic in hopes to gain a clearer picture of how satellite galaxy M33 is going to inspiral and eventually merge with the merged product of the Milky Way (MW) and M31. It is currently unclear if there are resonances created as result of satellites passing the the dark matter (DM) halo. Finding out more about the wake could help elucidate that. Resonances, as discussed by (Weinberg 1998), are caused when a clustering of particles in the halo effect the inner regions of particles, particularly the disk of a spiral galaxy.

In previous literature, Mulder in 1983 attempts to show the effects of DF by modeling an ideal case where a point mass moves through a Maxwellian Distribution sea of particles. The point mass is less in size than the entire surrounding sea of particles. In Figure 1, we see that there is a general over density in the plot directly behind the point mass. It can also be noted that the over density

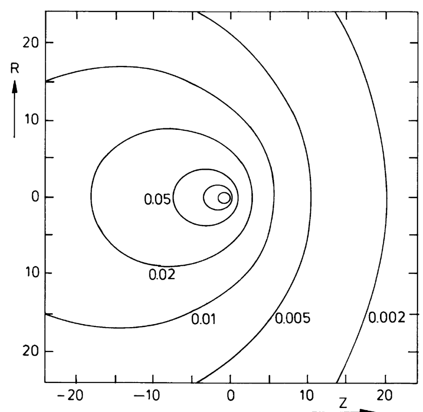

Figure 1. Over density plot of a point mass traveling through sea of particles in two dimensions. The numbers located on the contours refers to the ratio of local over density subtracted by the average density of the sea. From (Mulder 1983).

begins appearing in front of the mass and then expanding outward. However, the simulation is only modeling the system in two dimensions and so therefore is not accounting for a third dimension. This points us in the right direction and allows us to gain idea of where to look for the desnsest part of the wake. Figure 1 is what we will be trying to replicate with the modification of being it in 3 dimensions.

We expect to see a wake roughly equivalent in size at the end of the simulation. This idea was put forth by (Mulder 1983). As time passes while the mass travels through the medium, it begins to build a wake behind it. This wake then contributes to the mass of the passing body and consequently amasses more particles in the wake. During this time, the body is slowing down from wake since is acting as a drag force. The slowed body then has more time to interact with the surrounding medium, drawing in more particles. The snowball-like

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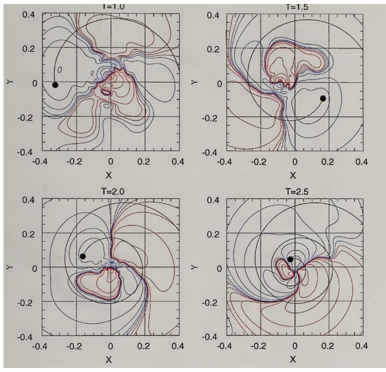

Figure 2. Over density plot from Choi showing inner and outer wakes in two dimensions. Red contours refer to an over density and blue refers to an under density. The black line represents the trajectory of the point mass inspiraling. From top left to bottom right the time is progressing forwards. From (Choi 2007).

effect will continue until the mass of the wake is roughly equivalent to the mass of the body. At this point, the wake is pulling back on the body with such force that the velocity of the body will then likely slow to the ambient velocity of the medium.

Additionally, Weinberg conducted a handful of studies where he investigated DF and how it related to the wake and sought to answer how resonances in the halo might effect the disk. The conclusion was that as a satellite passes through the halo, it localizes particles to the path taken by the satellite, the over density in turn can create distortions in the disk of a spiral galaxy (Weinberg 1998). Weinberg also shows that warping can happen in disks and notes that the warp happens after some lag time because the disk needs time to respond to the changing halo due to the generally large distances from which the gravity is felt (Weinberg 1998). This warping is characteristically at opposite edges of the disk (Weinberg 1998).The causes of warping can occur for a number of reasons. The main four reasons of warping are from excitation in the halo, gravitational noise in the halo, the Coriolis force the disk, and tidal fields from satellites according to (Nelson & Tremaine 1995). We will only be concerned with the excitation in the halo for this paper.

2. THIS PROJECT

For this project, we sought out to determine if the gravitational wake could be seen at all from our analysis. We wanted to answer if the wake was noticeable at the resolution of one million particles and if we could determine any tendencies for resonances within the halo based off of the path taken by M33.

The question of whether the wake is visible is a question and check for the simulation that we are using given by (van der Marel, Besla 2012). In the best case scenario, we would be able to emulate the simulation provided in the thesis of (Choi 2007). In this thesis, and exampled in Figure 2, we can identify an inner and outer wake. However, it is hopeful that we could be able to see its minute effects in the simulation.

The question we hope to answer with this project is how apparent the wake will be through the simulation presented by (van der Marel, Besla 2012). This is critical for analysis because it will lead us to have a better understanding of what is happening to M33 as it orbits in the dark matter halo.

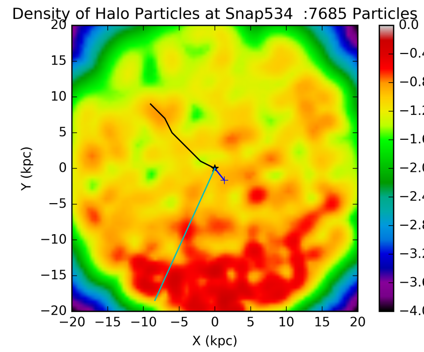

Figure 3. Plot of the combined halos of MW and M31, where M33 is at the center. The black star represents the COM of M33. The blue line with a plus symbol at the end is a scaled representation of the 2-D velocity. The green line is pointing to the COM of M31. The black line is showing the previous path of M33. The colors are a logarithmically scaled density of the combined halo. The densest part will be red/white and the least dense will be purple/blue. In the top right, the number of particles enclosed is listed. This is a 2 dimensional representation in the XY plane

3. METHODS

For this project, we used the simulation presented by (van der Marel, Besla 2012). In the highest resolution form of the simulation by (van der Marel, Besla 2012) is on order of one million particles. This simulation is thought to be to most accurate simulation of the merger sequence between M31 and the MW to date. However, it may have too few in particles in order to definitively exhibit the characteristics of the wake for M33. The simulation fully includes the different components of the MW, M31, and M33. For the purposes of this project, we only consider the dark mater halo from the MW and M31. We do not include the disk or bulge particles of any galaxy.

The code I have written for this analysis was written in Python. It takes the center of mass (COM) of the M33 and M31. It then subtracts out the COM position of M33 so it appears as if M33 is always at the origin our plot. Figure 3 shows the bulk of the functioning part of the code. The code combines the halos of MW and M31 and then looks at the surrounding area defined by the COM of M33, sweeping out to a radius of 25 kpc. In Figure 3, the color scale shows the more dense areas in red/white. It also is able to compute the velocity of M33 and project it, given as the blue line ending in a plus sign. It then also points to the COM of M31 (green line). The code then calculates the path where M33 has previously been (black line). It is also able to iterate this process over all 800 snapshots given by (van der Marel, Besla 2012). The 800 snapshots roughly translate to timsteps of 14 Megayears per snap and therefore iterate starting from today's orientation to 11.5 Gigayears in the future.

To help create the plot shown in Figure 3, we used the assistance of (Garavito 2016), who allowed to us utilize a smoothing function he created. This function uses kernels, a nearest neighbor technique, and an algorithm established by (Jing & Suto 2002). The function looks at each particle and it's nearest 32 neighbors and then assigns a density value per area that was enclosed. It then iterates over the entire scope of particles to smooth out the density.

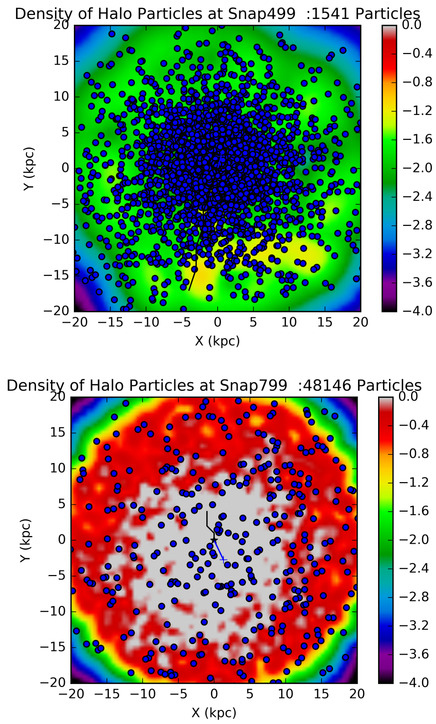

Figure 4. Plot similar to Figure 3. This is taken at two different times: Top - Snapshot 499 (approximately 7.5 Gyr) and Bottom - Snapshot 799 (approximately 11.5 Gyr). Here we have also overplotted the dark matter particles of M33 (blue dots) to illustrate the change in grouping.

4. RESULTS

We have composed an animation of the snap shots in sequential order to help illustrate the appearance of the wake. There are two distinct animations where one has the color scale fixed and the other is free to scale to the local density. Both of these animations do not appear to show definitive wake-like features. If we look directly behind the COM of M33 in Figure 3, where behind refers to 180 degrees opposite the velocity vector (blue line), the main features of a wake are not readily apparent.

In Figure 3, there is a distinct red area toward to bottom of the image with a gradient to yellow as you move towards the top. This feature is reflecting the denser area of the combined halos and as you move radially outward, the density decreases. Here we can utilize the the green line which shows the COM of M31 which helps us gauge the COM of the system. The animation shows this type of feature frequently and it is an expected result.

The unfixed animation occasionally shows features resembling what could be a wake but this is likely a result from the local inhomogeneities of over and under densities of the halo. The fixed scale animation does not show any noticeable features of the wake because the scale may be too large for such a small effect.

In Figure 4, I have given a similar plot to Figure 3, with the addition of the DM particles of M33 over plotted. The figure shows two time steps during the simulation. In the bottom plot (the later time) of Figure 4, the distribution of particles is severely spread out, whereas the top snapshot in taken from the middle of the simulation shows the DM particles are more tightly grouped.

5. DISCUSSION

What do these results mean? Does the absence of the wake in our results mean it does not exist? Data from (van der Marel, Besla 2012) show that M33 is on an inspiraling orbit and is steadily decaying, so we know that the satellite is slowing down. Eventually it will completely merge with the MW-M31 merger. Therefore, we know it is interacting with the DM particles and a wake is created. Otherwise, it would remain in a steady orbit. The wake not being found is likely due to an incomplete analysis of the system and because M33 is extremely separated at the end of the simulation, as displayed in Figure 4. The tidal forces on M33 have significantly stretched out its shape so that it can hardly be treated as a point mass any more. The idealized cases put forth by (Mulder 1983) and (Weinberg 1998) only account for moving point masses and only in two dimensions. Therefore, it comes with little surprise that when we look for the wake, it is obscured and difficult to distinguish from the surrounding particles.

We have learned that the halo features are harder to see and to distinguish than the idealized cases. The results we have found mean that we need a better way of selecting and showing the particles that have been perturbed by M33. The implication of this result means that more analysis of the wake is needed.

The importance of our findings lead us to conclude that a three dimensional analysis of idealized systems is needed to better point us to where the wake should appear. The importance of finding the wake can lead us to find where resonances can lie in the halo. The clustering of the particles, as mentioned earlier, can cause warping, often symmetric, in the disk. We see this type of effect in the galaxies ESO 510-13 and NGC 4013. If we can pinpoint the causes of the warping then we can then have better models to predict the shapes of galaxies. This is also very powerful since galaxies evolve on such slow timescales relative to a human life. If we are able to take a picture of a galaxy today and it has a characteristic warping, then we might be able to say more about the satellites or other nearby galaxies that are interacting with it. The amount of warping, discussed heavily by (Weinberg 1998), might even be able to shed light as to the mass or orbit of the smaller body of the parent galaxy. In relation this project, however, the analysis of the warp was not considered.

6. CONCLUSION

In this paper we have examined the simulation from (van der Marel, Besla 2012) to look for the effects of DF in the form of a gravitational wake following M33. The investigation of the gravitational wake is an important endeavor to help us better understand the morphology of galactic evolution. As mentioned in the last section, the wake from satellites can have a non-negligible effect on the halo and consequently on the disk of a spiral galaxy. We can measure this effect to possibly gain an understanding about smaller orbiting bodies or even learn about the halo.

We explored the possibility of a gravitational wake by measuring the population density of the combined halos of the MW and M31 around a localized area defined by the COM of M33 at each time step for roughly 11.5 Gyr into the future. The animations included with this paper, particularly the fixed scale animation, were not able to distinctly show a wake. A wake was expected to be visible within ten or twenty kiloparsecs of the COM of M33, in retrospect this estimation is likely incorrect. Therefore we are not able to say that we have conclusively identified a wake behind M33 and cannot speculate on the morphology of M31's disk or the morphology of the merged galactic system.

In future work, different analysis should be employed. It might be feasible to adopt a Hernquist profile (before the merge) for the halo. One could subtract out the mass given by the profile at the radius of the COM of M33 and then plot the remaining mass. Another avenue to pursue could possibly taking the local average density then subtracting that out from the mass. Although, the best option might be to search for the wake in a wider range of particles. In this instance, we took a spherical shape around the COM of M33. The better idea might be to plot a cylinder in the projection of the plane of orbit that lags behind the half-mass of the M33 system.

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For additional supplemental material visit https://github.com/yinglingw/ASTR400B.

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