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The Fate of Baryonic Matter in the Tidal Streams of the MW-M31 Merger

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ABSTRACT

The tidal interactions of merging or closely approaching galaxies throws material outwards from the galaxy forming tails, streams and bridges. The results of these tidal interactions can give clues to the history of a galaxy's evolution, particularly whether it had any close flybys or mergers in the past. My question was to find when outlying tidal structures of the Milky Way and M31 first form as they approach and merge, and find out if the mass thrown out into intergalactic space is a significant portion of each galaxy's baryonic mass. The first question can give some hints about how tidal structures far from the center of mass begin forming, while the second can identify if mass lost because of mergers is a significant process in determining the evolution and fate of galaxies. I found that for the Milky Way, significant tidal structures beyond the Jacobi radius began forming only on the final approach in the merger with M31, while M31's tidal structures formed on the first near flyby. I also found that the Milky Way and M31 each lose 1.3e9 M_Sun and 1.73e9 M_Sun as they merge.

Keywords: Jacobi radius, galaxy merger, tidal tails, tidal bridge, merger remnant, gravitationally bound, major merger

1. INTRODUCTION

Interactions between galaxies can create structures such as tidal tails and tidal bridges, which are thin regions of baryonic matter (gas and stars) extending out from the galaxy into intergalactic space or towards another galaxy. Theses structures are formed by and named for the tidal forces two galaxies experience, either during a galaxy merger as the galaxies combine into one gravitationally bound object, where the energy of each galaxy's matter isn't enough to escape the gravitational pull of the other. Tidal structures can also form during a galactic flyby where the galaxies approach close enough to tidally interact without becoming gravitationally bound to each other.

Tidal structures help describe the kinematics and distribution of the necessary but poorly understood component of every galaxy: the dark matter halo(Willman & Strader 2012). The existence of tidal features can indicate that a now isolated galaxy once interacted with a another galaxy and/or merged, which may not be obvious from its appearance. The history of a galaxy and any possible mergers can tell the history of the galaxy's evolution by explaining the galaxy's history of star formation and gas exchange. Morphological evolution is also explained through tidal interactions, as many structures in elliptical or lenticular galaxies such as stellar shells are attributed to mergers (Ji et al. 2014). Finally, some dwarf galaxies (tidal dwarf galaxies) may be generated from stellar tails Kroupa et al. (2010).

The current understating of the topic places tidal tails/bridges as a result of flybys or a merger with another galaxy of similar size, the latter cases being referred to as a major mergers. Tails tend to form in any interaction but seem more pronounced in flybys, while bridges are more common during major mergers, though exceptions exist Toomre & Toomre (1972). Tidal features last far longer further away from the center of the galaxy, because of the longer dynamical time at greater distances. The material in the tidal tails tends to be older stars, and while mergers can trigger star formation, it appears the new stars stay in the resultant galaxy's central regions Ji et al. (2014). The stellar tails tend to intersect or be completely subsumed by the dark matter halo, and as such the length and prominence of the tails are inversely proportional to the depth of the halo's mass. Generally, tidal tails remain gravitationally bound after a merger, although a few stars may escape. Figure 1 from Alar Toomre's touchstone paper on the subject (Toomre & Toomre 1972) demonstrate through simulations of galactic interactions that the structures observed in the galaxies such as the Antennae Galaxy can be explained through tidal forces only. The primary takeaway from the figure, and the paper in general, is that the primary impetus for the creation of bridges and tails is indeed the tidal forces, and that other phenomenon may safely be ignored as a first approximation.

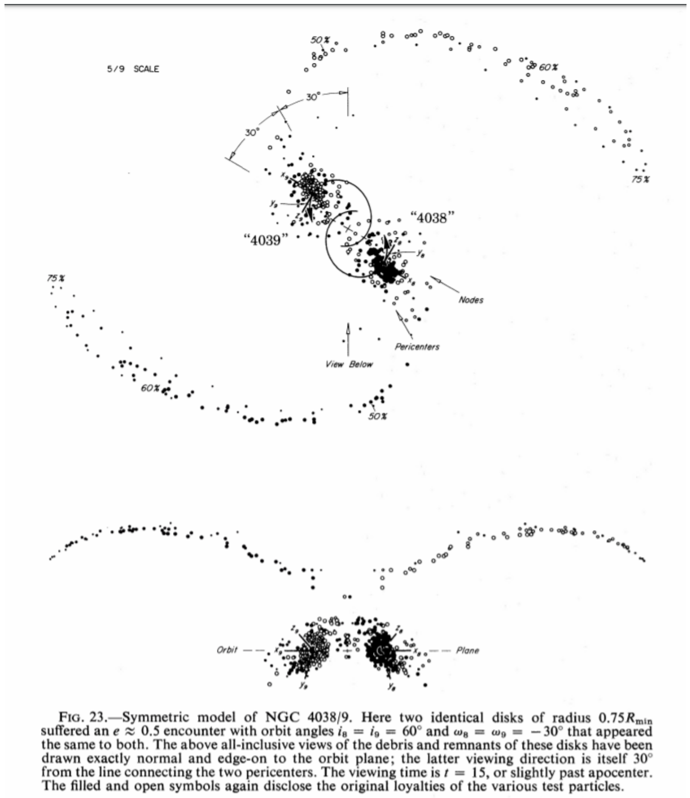


Figure 1. Image taken from Toomre 1971 showing an interaction's ability to form the structure observed in the antennae galaxy. At the time of the Toomre paper, it was thought that such structure could not be formed by tidal forces alone. Toomre & Toomre (1972)

One current question in the field is exactly how long these tidal features survive and what effects their lifespan. The initial rotation of the galaxy compared to the incoming galaxy's trajectory, initial angular momentum and the contributions of star formation and supernovae have been included in simulations calculating the lifespan of large features, but the effect of ram pressure, AGN, harassment, and nearby clusters of galaxies have not. Early galaxies are expected to have far more gas, and the addition of this gaseous material may alter the nature, shape, and lifespan of an tidal features compared to the gas poor galaxies and features that we observe (Ji et al. 2014). The types of galaxies that create tidal features, particularly around the Milky Way, is also open for debate. For example, the Sagittarius stream may have been a spiral galaxy instead of a dwarf (Peñarrubia et al. 2010). While galaxies appear to retain the vast majority of their mass during mergers and reactions, how much mass a tail or bridge loses exactly is not well known.

2. PROPOSAL

In this project, I will be tracking and visualizing the creation and growth of the tidal structures arising from the major merger between M31 and the Milky Way. I want to find out when the structures form, and how much stellar mass escapes from the new combined galaxy as a result of the interactions.

This project will help to address which tidal structures originate from major mergers, especially in the case of the Milky Way and Milky Way-type galaxies. The project will also predict the mass lost by the M31-MW system in the course of the merger.

The first question can help identify which galaxy morphologies we observe are the result of major mergers, which in turn can help us identify which galaxies have merged in the past. The second question can give a more quantitative answer to explain how much mass is lost with a merger, even if that mass loss is not expected to be significant.

3. METHODS

I am using the results of an N-body simulation (Willman & Strader 2012), in which the mass, position, and velocity of each particle (of which there are N) in each galaxy is documented as M31 and the Milky Way merge. The simulation also differentiates based on the origin or type of particle- disk, bulge, or halo. The simulation returns the kinematic information of each particles at different times during the merger. These different times are numerically sequenced and are called snapshots.

By using the information taken from this simulation, I hope to identify which particles comprise tidal structures, and which particles have escaped the merger. The outliers that end up comprising the tidal structures can be found by computing the Jacobi radius, outside which is considered beyond the boundary of the galaxy and also serves as a cutoff for which particles have escaped. Using this method also requires acknowledging and working around the fact that the Jacobi radius doesn't work once the galaxies are too close or have merged. I will thus need to find the time at which the mass within the Jacobi radius diverges. Note also that the Jacobi radius is calculated assuming the galaxy is an isothermal sphere.

My code will need to compute the Jacobi radius to identify which particles fall "outside" the galaxy. The equation

$$R_j = R\frac{m}{2M_{Enc}}$$

gives the Jacobi radius as a function of the particle's mass m, its distance from the center of mass R, and the mass of the host object enclosed at the particle's radius M_{Enc}.

The plots I am hoping to create will first be a density map of the tidal structures, picked out via the methods explained above. An example of the density plot I'm hoping to make is given in Figure 2, although without a a specification of tidal particles. This will help me figure out when the tidal structures being to propagate out beyond the Jacobi radius. Another plot I've already mentioned in the total mass lost as a function of time. By simply looking at the total mass lost at the final snapshot, I can just pick out the mass lost over the merger as a whole. The only reason to graph this instead of just computing the answer is so I can also figure out when the mass is gaining enough speed to escape. Finally, a third possible plot is the mass outside the Jacobi radius as a function of time. This will give me the same information as the first plot, but in a more quantitative sense then just looking at a picture and guessing what happens to the structure. By comparing the total mass lost and total mass outside the Jacobi radius at the final snapshot, I can figure out what happens to tidal structures-do they escape, spiral back in, or last longer than the simulation ran for.

I'm not expecting a significant amount of mass loss in either the MW or M31, and I also suspect that the first tidal structure will form at the first very close approach at around 4 Gyr.

To preserve time and computing power, I will only run my code on an interval of snapshots where the galaxies are close together, as this is when tidal features should begin to form. By looking at the distance of the two galaxies as a function of time, I can pick out when that interval should be. I want to include the first close approach and the beginning of the final merger, and based on Figure 3, that corresponds to snap ID 250 to 450. I will also only look at one in every ten snapshots, again to conserve computing power and time.

4. RESULTS

Figure 4 displays density diagrams much like Figure 2, but I have completed the step of locating only the particles that are outside the Jacobi radius of the Milky Way as it rotates Andromeda. The first diagram displays the particles outside the Jacobi radius at snap ID 280, the next at 390, and the last shows the particles at snap ID 400. This plot was instrumental in showing where the Jacobi radius methodology for selecting escaped particles breaks down: around snap ID 410. Furthermore, this plot (and the plots for lower snap IDs in general) demonstrate that notable outlying tidal structure is slow to form, and only beings to appear when the galaxies start spiralling in towards each other.

Figure 5 shows the amount of mass that has escaped from the Milky Way at each snap ID. This plot also shows the Jacobi radius method breaks down around snap ID 400, after which the radius starts shrinking and the "escaping" mass gets huge. The mass lost at snap ID 390 is taken for the total mass lost: 1.3e9 M_Sun.

Figures 6 and 7 are the same idea for each graph, but with M31 instead of the Milky Way. (code is still running). Note that on figure 6, the mass lost spikes up earlier for M31, around when the two main galaxies approach close to each other. I am not sure what the cause of this is (possibly interactions with M33 leading to an enhanced tidal response to the first flyby) so I took the mass lost at snap ID 280, which is 1.73e9 M_Sun.

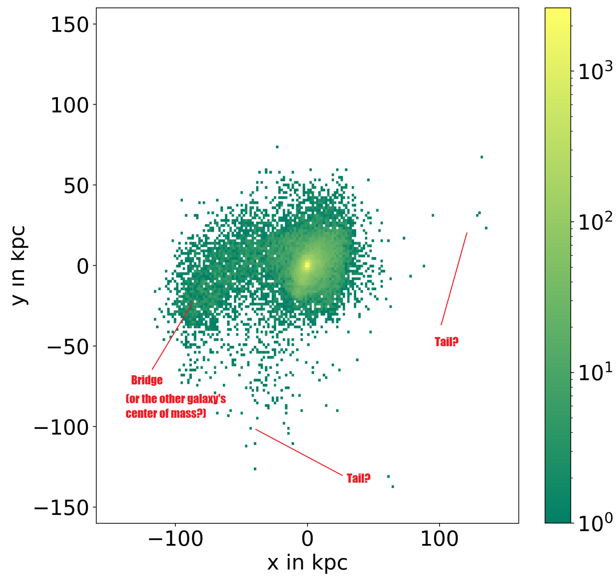


Figure 2. First test taken from MW_450 to see if any obvious features fall out of the density plot.

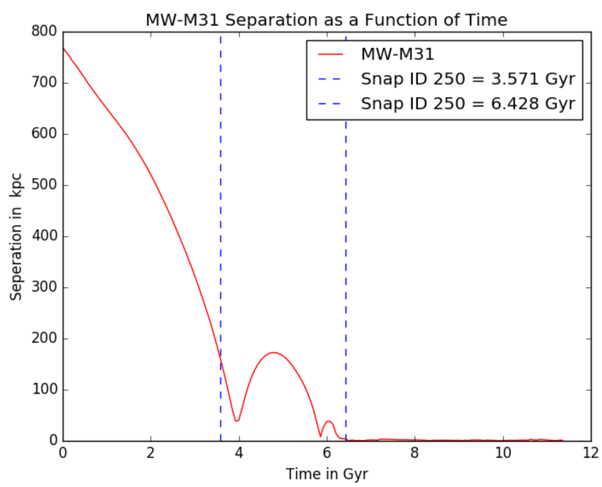
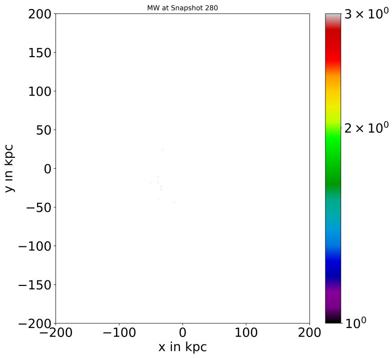


Figure 3. A plot showing the distances of the center of mass of M31 and the Milky Way. The time enclosed in the blue dashed lines is what my code was run with, corresponding to snap ID 250 to 450.

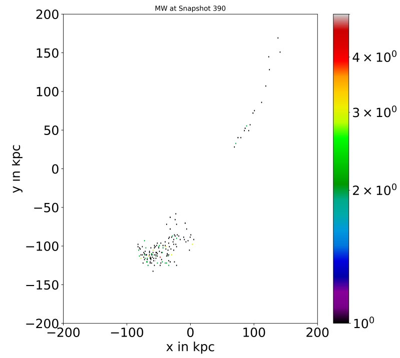
5. DISCUSSION

The first result- that almost no significant outlying tidal structure forms in the MW as a result of the close flyby before collision but does form in M31, does not agree with my original hypothesis. Note that this doesn't mean there is no tidal structure for the MW, just that none or very little of it is outside the Jacobi radius. This suggests that for stretched out/distance tidal structures to form and for any mass loss at all, two galaxies must approach very closely, and in this case be on their way to colliding. Or it could mean that some other influence must be present, like M33 in the case of M31.

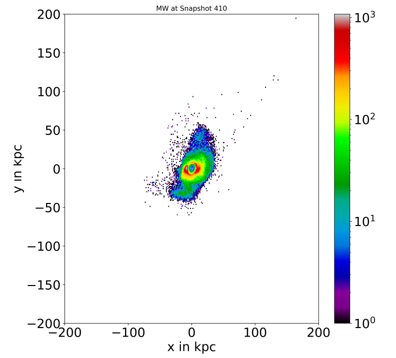
The results concerning the total mass lost are in line with my hypothesis, and the general expectations in the field as explained above. The baryonic mass lost amounts to below 2% of the total mass of the MW disk or .014% of the



At snap ID 280, the two galaxies have approached near each other, but are now moving apart. The tidal structure is present (otherwise there would be no particles at all to graph) but impossible to see clearly on the density histogram



The approaching galaxy has noticeable and significant structure at snap ID 390.



At snap ID 410, the density plot is beginning to show the galactic center.

Figure 4. Escaping particle density of histograms at different snap IDs. The axes give the location of each "bin" containing particles. The plot is centered on the Milky Way's center of mass. Significant outlying tidal structure does not form early.

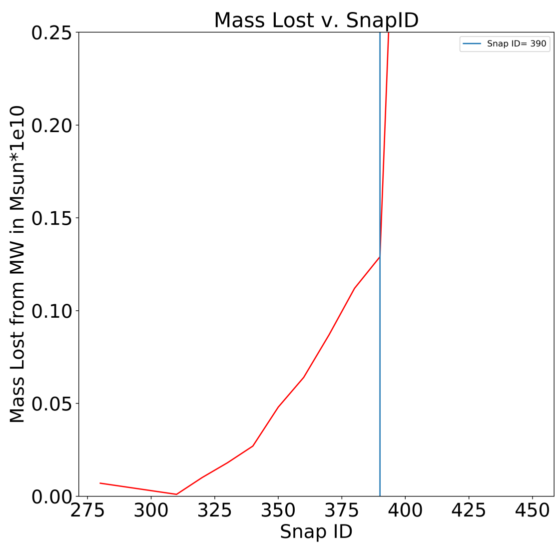
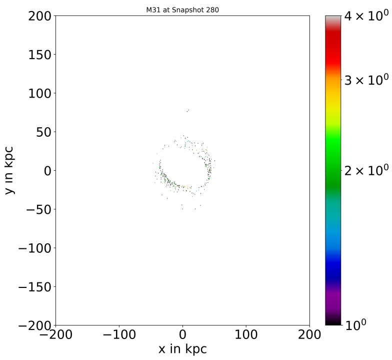


Figure 5. Plot of total mass lost against the snap ID (time). Note that because the particles that escape the galaxy are not removed the simulation, this plot shows the mass lost at each snap ID. By looking at the behavior of the graph, we can safely find a cutoff for when the Jacobi radius no longer becomes reliable, and use the y-value of the plot at that snap ID as the total mass loss. That is snap ID 390, which has a mass lost value of 1.3e9 M_Sun. Toomre & Toomre (1972)

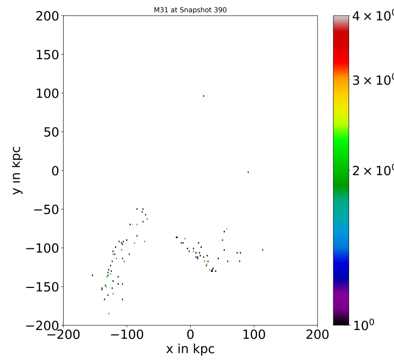
Andromeda Galaxy's disk mass (as given by Homework 3). We can then safely say that mass loss because of mergers or flybys is not significant in the evolution of galaxies, which agrees with the current expectation in the field.

6. CONCLUSIONS

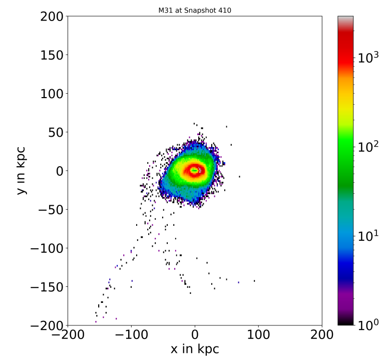
The evolution and formation of tidal tails out of visible baryonic matter as the result of mergers or flybys are one of the most visually striking features of galaxies, and these morphological features can suggest the paths and interactions the galaxy took to reach its present state. By locating the tidal structures thrown further out from the galactic core,



At snap ID 280, the two galaxies have approached near each other, but are now moving apart. The tidal structure for M31 is more visible in these earlier snapshots, possibly due to enhanced tidal interactions because of M33's influence.



The approaching galaxy has created noticeable and significant structure outlying tidal structure at snap ID 390.



At snap ID 410, the density plot is beginning to show the galactic center.

Figure 6. Escaping particle density of histograms at different snap IDs. The axes give the location of each "bin" containing particles. The plot is centered on M31's center of mass. Significant outlying tidal structure does not form early.

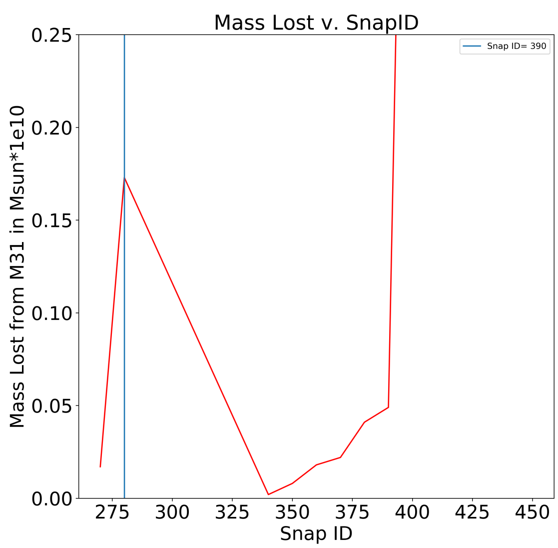


Figure 7. Plot of total mass lost against the snap ID (time). Note that because the particles that escape the galaxy are not removed the simulation, this plot shows the mass lost at each snap ID. By looking at the behavior of the graph, we can safely find a cutoff for when the Jacobi radius no longer becomes reliable, and use the y-value of the plot at that snap ID as the total mass loss. For M31, that is snap ID 280, which has a mass lost value of 1.73e9 M_Sun. Toomre & Toomre (1972)

I found an estimate of the mass lost as a result of the merger. Both the morphology observed and the mass lost can give insight into how galaxies evolve and gain tidal structures in general.

The results I got for the total mass lost from each galaxy were both negligible in comparison to the total baryon mass of each galaxy, as I expected. Furthermore, the mass lost in this merger (and in others, as seen in the literature) is so small that it has no effect on the evolution of galaxies.

However, the result that I got for the formation of tidal structures beyond the Jacobi radius was far more surprising. I originally suspected that the structure's would first form on the initial flyby of M31 and the Milky Way, but instead I found that significant structure forms for M31 only. This is the opposite of what would be expected, as the more massive M31 should better hold onto its mass and have less tidal structure. If anything, the Milky Way should have more noticeable structure beyond the Jacobi radius. I thought this may be the result of M33's tidal influence on M31- akin to how the extremity of the tides on Earth is a combination of solar and lunar influences. However, it is also possible that my code is somehow returning the right answer for M31 but not for the Milky Way, although the code itself does not change between each galaxy, merely the inputs. While the results are hard to trust in, they could suggest that the formation of tidal structure is heavily dependent on satellites even in the case of two approximately equal mass objects.

There are several improvements that I could make to the code to improve the final result found. The first and most obvious is simply increasing the time resolution of the script, by running it on more files. Right now, I am only looking at one in ten snapshots in the interval I'm concerned with. A difference of ten snap ID corresponds to tens of Myr per time step. For times when the galaxies are distant, this is acceptable, but when they get close they begin moving much faster relative to each other.Another important improvement is redefining the expression I used to compute the Jacobi radius. The current expression assumes mass is distributed in an isothermal sphere. This is a fine approximation for the bulge and halo, but for the disk of each galaxy, a Miyamoto-Nagai potential is more appropriate, although mathematically rigorous. Finally, calculating the escape velocity at each radius and comparing the velocity of each particle to see which ones escape out to infinity was my original goal, but didn't work because of coding issues. Physically it makes sense that the particles withe velocity greater than the escape velocity are going to have their masses ejected from the system, and in any case should be more bullet proof than the Jacobi radius method, which can't be used after the galaxies merge. In any case, it would be intriguing to see if the results from the Jacobi radius method and escape velocity method agree at nearer times.

7. ACKNOWLEDGEMENTS

I would like to thank Gurtina Besla and Rixin Liu for their guidance in the project, and the critical knowledge and skills they imparted. Thanks also to Jimmy Lilly.

Below is a list of libraries used in the project, followed by academic references.

- Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538-3881/aabc4f)
- matplotlib Hunter (2007),DOI: 10.1109/MCSE.2007.55
- numpy van der Walt et al. (2011), DOI : 10.1109/MCSE.2011.37
- scipy Jones et al. (2001–),Open source scientific tools for Python.http://www.scipy.org/
- ipython Perez & Granger (2007), DOI : 10.1109/MCSE.2007.53

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