Draft version May 1, 2020
Typeset using LaTeX default style in AASTeX62

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

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(Received March 19, 2020; Revised April 16, 2020)

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.

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.

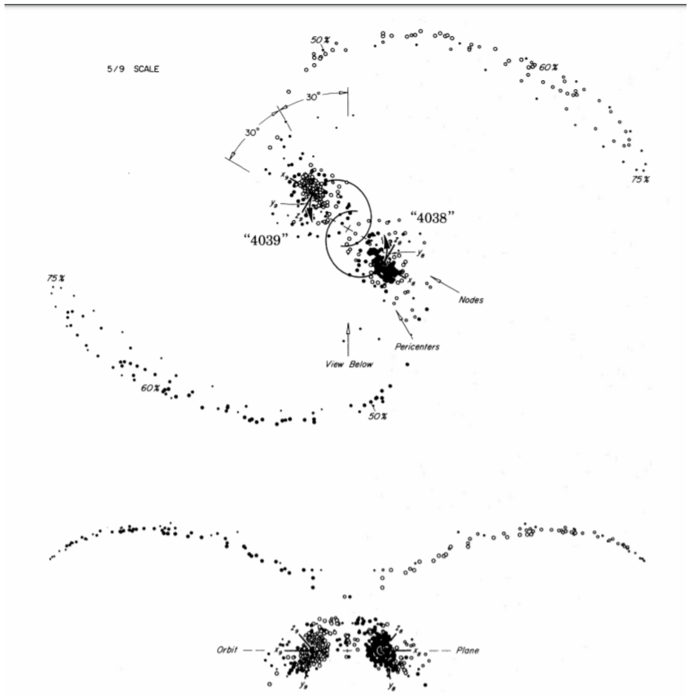


FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks have been drawn exactly normal and edge-on to the orbit plane; the latter viewing direction is itself 30° from the line connecting the two pericenters. The viewing time is $t = 15$, or slightly past apocenter. The filled and open symbols again disclose the original loyalties of the various test particles.

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)

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 survive, 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 stellar 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}. I must also calculate the escape velocity. Because the distribution of the matter in the galaxies is not perfectly spherical or idealized, the use of a more general equation for escape velocity is warranted:

$$V_{Esc}^2 = 2|\Phi|$$

Where Φ is the gravitational potential arising from the distribution of mass. For the bulge and halo, I will use the Hernquist potential (Hernquist 1990).

$$\Phi = -\frac{-GM_{Enc}}{R+a}$$

The parameter a is a scale length guessed based on the properties of the galaxy, and is 0.5 in the case of M31 and the Milky Way. For the disk, the Miyamoto-Nagai potential must be used (Miyamoto & Nagai 1975).

$$\Phi = -\frac{-GM_{Enc}}{\sqrt{R^2 + (a + \sqrt{b^2 + z^2})^2}}$$

The parameter b is a scale height, which for my purposes I will assume is a fifth of the scale radius.

The plots I am hoping to create will first and foremost 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 the final fate of the tidal structures, as I'll be able to see visually whether they spiral back in, continue orbiting, or so on. 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.

4. RESULTS

Figure 3 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 4 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 Msun.

Figures 5 and 6 are the same idea for each graph, but with M31 instead of the Milky Way. (code is still running)

5. DISCUSSION

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

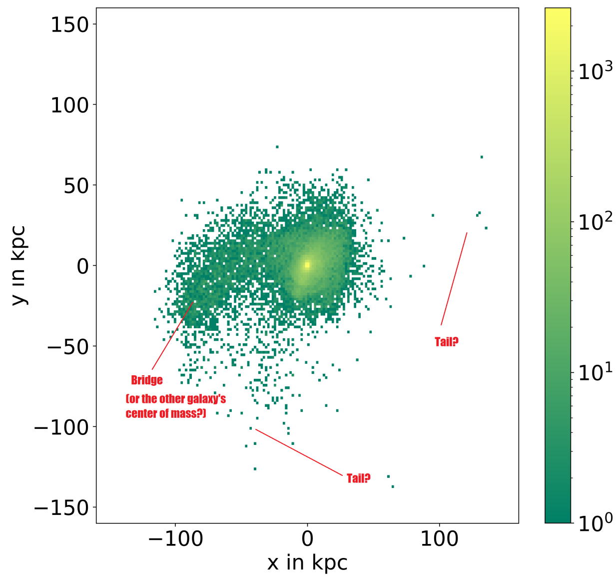
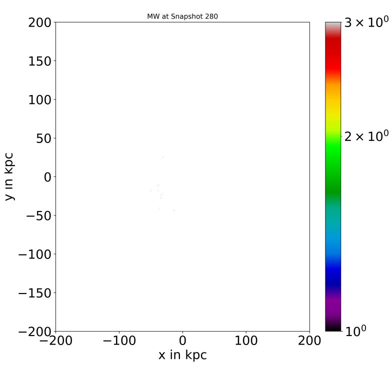
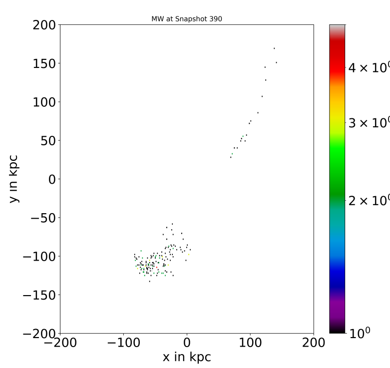


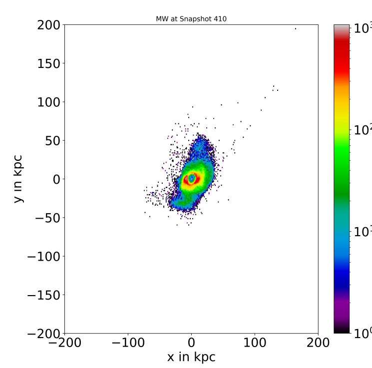
Figure 2. First test taken from MW_450 to see if any obvious features fall out of the density plot.



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 3. 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.

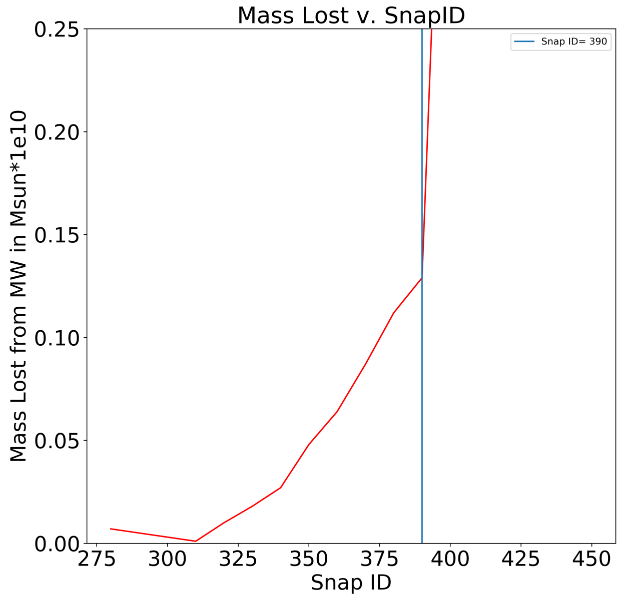
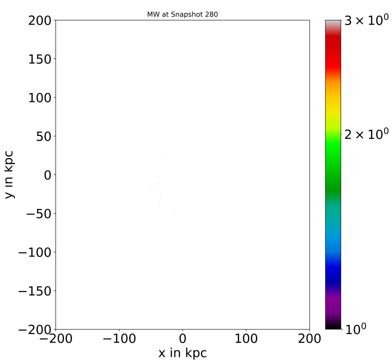


Figure 4. Plot of total mass lost against the snap ID (time). Note that because the particles that escape the galaxy are not removed the simulation, this plot shows the mass lost at each snap ID. By looking at the behavior of the graph, we can safely find a cutoff for when the Jacobi radius no longer 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 Msun. Toomre & Toomre (1972)



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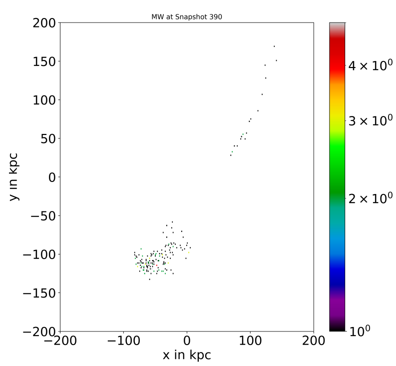

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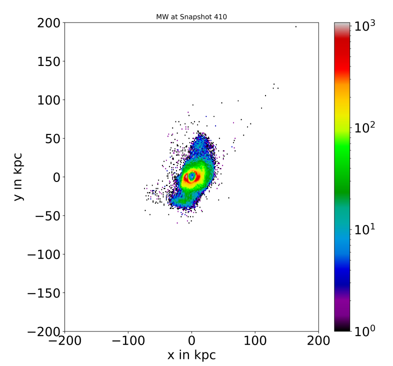

At snap ID 410, the density plot is beginning to show the galactic center.

Figure 5. 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.

The second result is exactly 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 (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.

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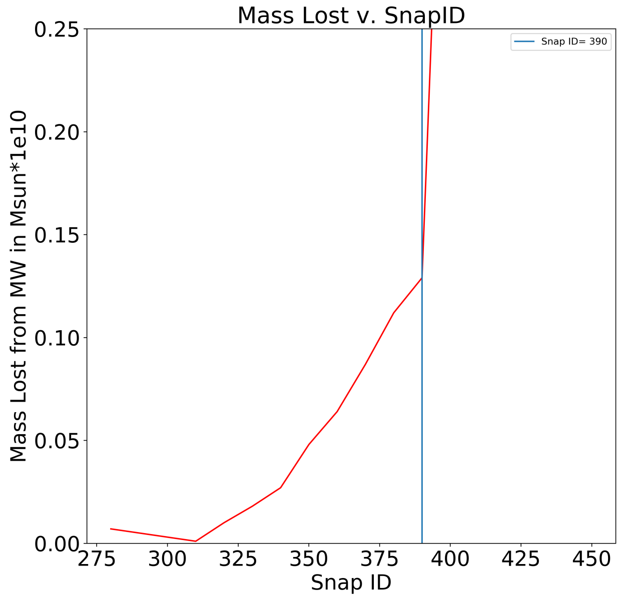

Figure 6. Plot of total mass lost against the snap ID (time). Note that because the particles that escape the galaxy are not removed the simulation, this plot shows the mass lost at each snap ID. By looking at the behavior of the graph, we can safely find a cutoff for when the Jacobi radius no longer 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 Msun. Toomre & Toomre (1972)

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