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

Steven Zhou-Wright[1]

[1] *The University of Arizona, Tucson, Arizona, USA*

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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.

2. PROPOSAL

In this project, I will be tracking and visualizing the creation, growth, and final fate of the tidal structures arising from the major merger between M31 and the Milky Way. I want to find out how long after the merger 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.

2.1. *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 sufficient velocity to escape the merged object. For the first part, 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. I can plot these particles and only these particles to get a much better resolved plot of the tidal structures and their density profile. Then, I can compute which particles has a sufficient escape velocity to unbind from the *combined* M31 and Milky Way system, those particles escaping with all their mass. I can use this information to graph the total mass lost as a function of time, or just get a numerical answer, as running the simulation over every snapshot for both galaxies could take too long. Figure 2 below demonstrates a first attempt to locate and describe tidal structures by graphing the Milky Way at snapshot 450. However, the presence of the "main" galaxy body effectively saturates the color density map and makes it difficult to see or describe tidal structures. This is why I want to use only the particles that are part of the tidal structure.

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. 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 compaing 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. Further, while I don't expect the tidal structures to survive in the long term, I don't believe the simulation will run long enough for them to move back into the new merged galaxy, because of the increased dynamical time. The simulation may see them getting closer to the center of mass, however.

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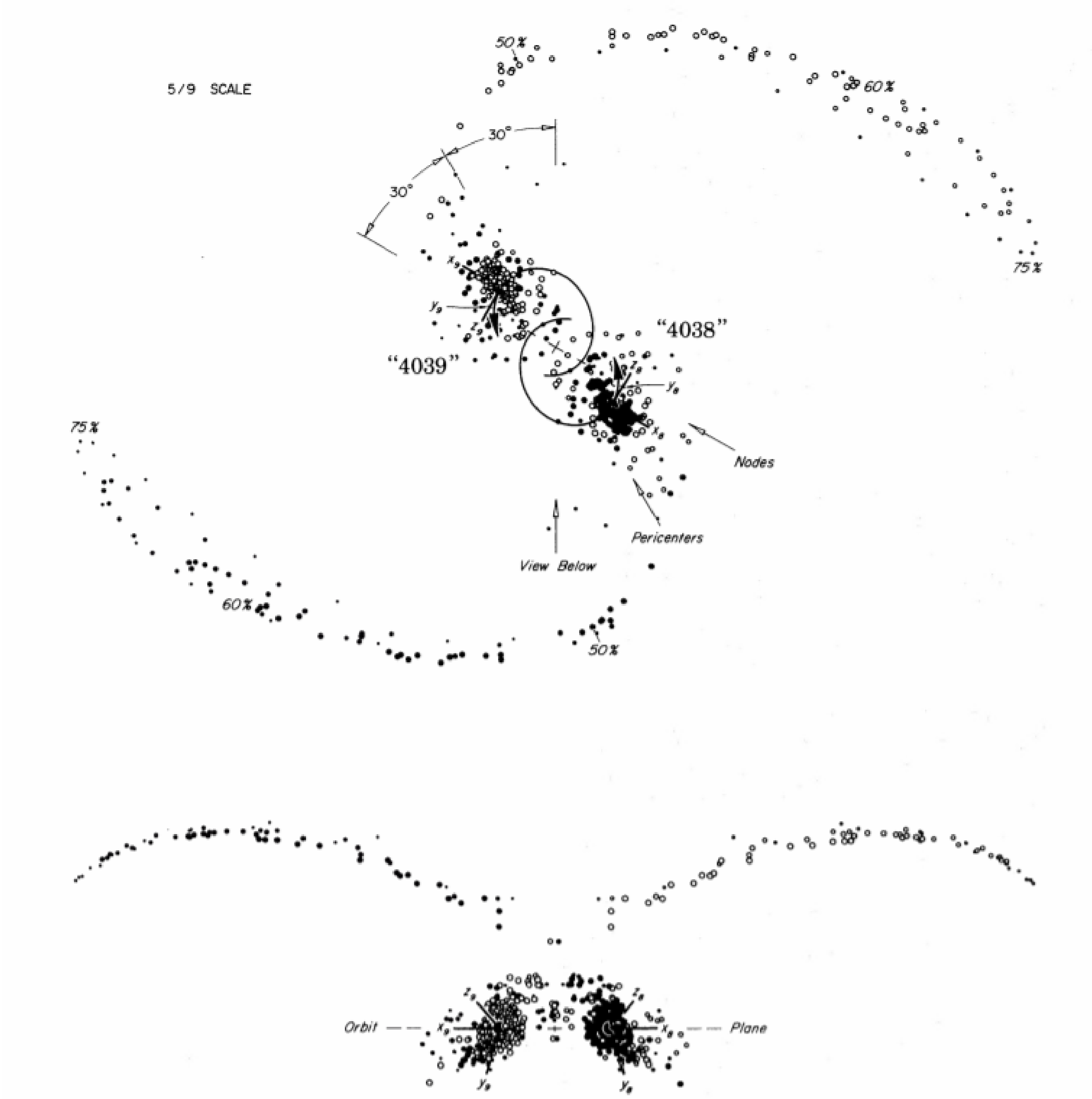

FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{\min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks 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)

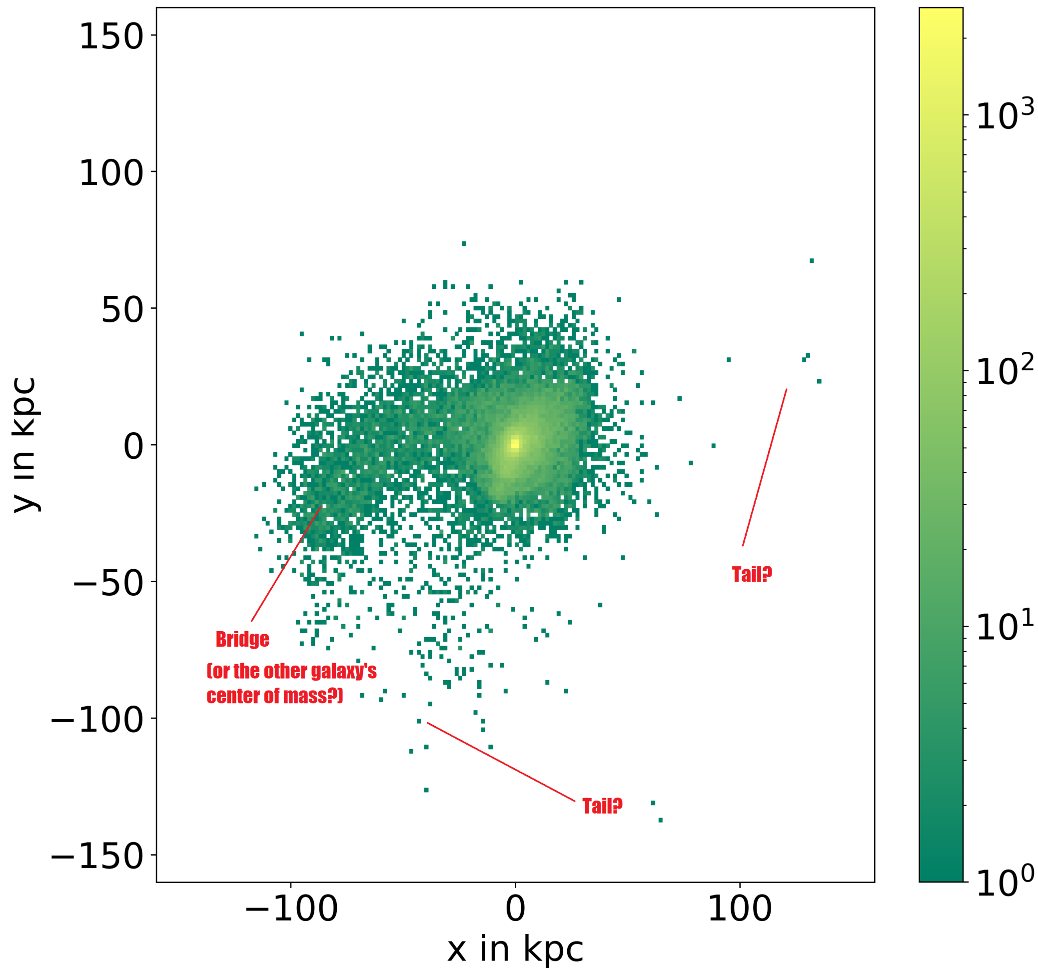

Figure 2. First test taken from MW_450 to see if any obvious features fall out of the density plot.