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Sweet Streams are Made of This: M33 Stellar Streams During and After MW/M31 Merger.

Ryan Webster[1]

[1] *University of Arizona, Department of Astronomy*

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1. INTRODUCTION

The collision and merger event between the Milky Way (MW) and Andromeda Galaxy (M31) is expected to begin four and a half billion years from now. During this event, the Local Group's (LG) third largest companion, the Triangulum Galaxy (M33), will most likely orbit around the larger two galaxies during and after the merger, with only a 7% chance of being ejected from the LG (van der Marel et al. 2012). Over the course of the merger, tidal forces from the MW and M31 are expected to strip stars, gas and dust from M33, creating tidal stellar streams. For my analysis, I will use the term "stellar streams" to refer to stars outside the Jacobi radius of their host galaxy, which form the trailing and leading tails.

Galaxies are defined as a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons and newtons laws of gravity (Willman & Strader 2012). Several mechanisms can cause galaxy evolution, including mergers, flybys, the evolution of its stellar population, and more. A prominent factor, and the focus of this study, is the interactions between a galaxy and its satellite. As these satellites approach the pericenter of their orbit around their host, the tidal forces between the two bodies are maximized, and stellar material at the Lagrange points is stretched out to form streams. These unbound stars create filament structures that lead and trail the satellite. With the help of large sky surveys like the Sloan Digital Sky Survey and Gaia, several examples of stellar streams have been found around the MW (Grillmair 2009). Their progenitors are commonly found along the stream and are typically dwarf galaxies or globular clusters. Other surveys, like those conducted by (Martínez-Delgado et al. 2010) reveal stellar streams around other galaxies in our local universe. This indicates that satellite in-falls are not exclusive to the MW, and are a common evolutionary characteristic for many, if not all, spiral galaxies in the universe.

There is no literature discussing stellar streams coinciding with an on-going galaxy merger, as most research focuses on a singular galaxy surrounded by a satellite. However, I believe these studies will still provide an appropriate starting point for my analysis. In particular, several studies using N-body simulations of galaxies with satellite in-falls have explored how the morphology of the resulting streams is effected overtime by gravitational influences from the two bodies. (Amorisco 2016) found a relationship between the kinematics of stars contributed by a satellite and the mass of the satellite. Since massive satellites lose angular momentum to dynamical friction, the stars in their streams have less energy and a lower velocity dispersion. The angular momentum lost by smaller systems is much less significant, so their streams have a higher velocity dispersion.

N-body simulations from (Choi et al. 2007) investigated the dynamics responsible for creating tails from dwarf galaxy interactions. They found the morphological asymmetry of the leading and trailing tails arises when the points of balance between the attractive force of both the host and satellite do not occur at equal distances from the satellites center. They also found that the satellite's gravity accelerates the trailing filament, and decelerates the leading filament, creating differences between unbound material and satellite orbits. This is seen in Figure 2, below. This also means the leading tail is located well inside the satellite's orbit, while the trailing tail is well outside the orbit. These are valuable insights for understanding what M33's stellar streams will look like in the simulation.

ryanwebster@email.arizona.edu

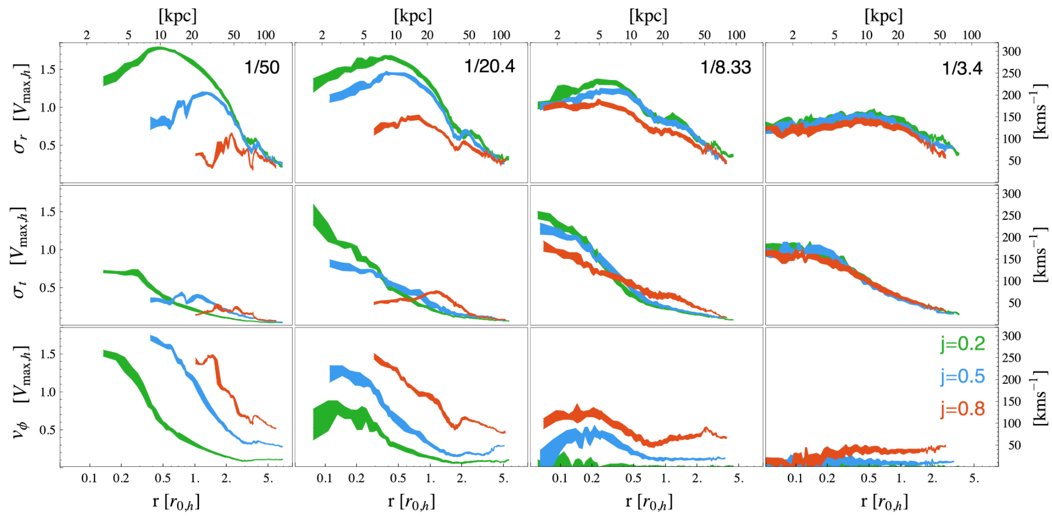

Figure 1. Figure 10 from (Amorisco 2016) showing the velocity dispersion of different satellite masses. Each column reflects a different value of $M_{vir,s}/M_{vir,h}$. The value "j" represents the initial angular momentum the satellite had upon approach to its host. I expect M33's velocity dispersion to closely resemble the last column, since $M_{vir,s}/M_{vir,h} \approx 1/3.4$ for M33 and M31.

2. THIS PROJECT

My research project aims to evaluate the morphology and evolution of M33's stellar streams over the course of the MW/M31 merger. To do this, I will use the velocity dispersion and kinematic parameters of stars outside the Jacobi radius of M33.

Given that many studies focus on the galaxy/satellite pairs that are not undergoing a merger, my analysis of M33's streams will incorporate new dynamics not previously explored. Comparisons between the findings of these studies and my analysis will provide insight into the complexity of stellar streams in exotic environments. It will address the effect that two large gravitational bodies have on the evolution of a smaller system's stellar streams.

3. METHODOLOGY

In order to accurately predict the LG merger and M33's streams, I will be using simulation data from (van der Marel et al. 2012). N-body simulations calculate the gravitational forces between multiple particles at several instances in time. They are useful for predicting the future behavior of systems with multiple discrete particles.

I plan on studying M33's stellar streams by finding simulation particles outside the Jacobi radius of M33 at each snapshot in the simulation. From here, I will address three main characteristics of the stream:

1. Velocity Dispersion: As in Figure 1, I will examine the stream's radial and tangential velocity components to see whether the stream is radially biased. M33 falls into the massive satellite regime, so I will investigate the low velocity dispersion and loss of angular momentum predicted in (Amorisco 2016). This should be apparent in the radial velocity dispersion of M33 as it orbits the merging galaxies. (Amorisco 2016) suggests a radially biased stellar population, which is characterized by a high radial velocity, is caused by a massive satellite in-fall.

2. Morphology: The degree to which streams trace the orbit of the satellite galaxy is explored heavily in (Choi et al. 2007) As discussed previously, the shape of the stream's leading and trailing tails are influenced by the satellite's self gravity. These effects should be visible in the merger simulation.

3. Formation: The formation of stellar streams is dependent on the tidal forces between the satellite and its host, which means its influenced by the host's gravitational potential well. The potential well between MW and M31 will evolve over the course of the simulation, getting deeper as the two galaxies merge. I aim to analyze when and how M33's streams begin to form around this evolving system.

The Jacobi radius of a satellite galaxy is given by:

$$R_j = R_{h/s}(M_s/2M_h)^{1/3} \tag{1}$$

Where R_{M_h/M_s} is the host and satellite separation, M_s is the bound mass of the satellite, and M_h is the mass of the host extending out to the barycenter of the satellite. As the local group evolves, so will the Jacobi Radius of M33. To account for this, I will calculated three Jacobi radii at each snap shot. The first being R_j between M33 and M31, then between M33 and the MW, and finally between M33 and M31/MW center of mass. Of these three, I will select the smallest R_j to find stream particles. I will then find M33 disk particles beyond that radius to isolate the streams.

For each iteration, the previous value of R_j will be used to calculate the enclosed mass of M33, which is used to calculate R_j and the cycle continues. To bootstrap this sequence, the initial R_j used is the distance between M33 and M31 at the beginning of the simulation.

For my dispersion analysis, I begin by binning all particles by their $\vec{r_i}$ and $\vec{v_i}$ values and then find their radial and tangential components via:

$$\hat{r_i} = \frac{\vec{r_i}}{\|\vec{r_i}\|} \tag{2}$$

$$\vec{v_{r_i}} = \hat{r_i} \cdot \vec{v_i} \tag{3}$$

$$\vec{v_{ti}} = \sqrt{\vec{v}^2 - \vec{v_{ri}}^2} \tag{4}$$

The dispersion is found by taking finding the variance of all $\vec{v_r}$ and $\vec{v_t}$ in their respective radius bins.

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^{N}(\vec{v_{r_i}} - \mu_r)^2}{N}}, \sigma_t = \sqrt{\frac{\sum_{i=1}^{N}(\vec{v_{t_i}} - \mu_t)^2}{N}} \tag{5}$$

The main plot I will create will be similar to Figure 1, where Equation 5 is plotted as a function of radial distance from M33's CoM. I will use it to test the predictions made by (Amorisco 2016). The other plot will be a visualization of M33's leading and trailing stream tails, akin to Figure 2. The second plot will show how well M33's orbit is traced by it's stream and the asymmetries of the stream itself.

My prediction is the streams will not closely follow the orbit of M33. The evidence for a morphological asymmetry during satellite in-falls, especially for massive systems, is strong from (Choi et al. 2007). I also predict that the added dynamics of a MW M31 merger will complicate the dynamics of the stellar streams, making many of the predictions from (Amorisco 2016) difficult to observe.

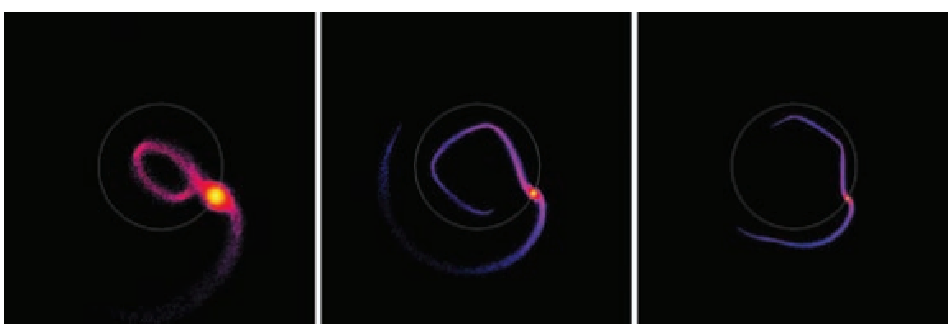

Figure 2. Figure 8 from (Choi et al. 2007) showing streams plotted against the orbit of the satellite. From left to right, the panels are for massive, low-mass and tiny-mass satellites. I expect M33 to exhibit the behavior of the massive system.

4. RESULTS

Using the low resolution files, I generated stream data from 160 snap shots in the (van der Marel et al. 2012) simulation. Figure 3 is a plot of the stream's velocity dispersion at Snap ID: 465 using Equation 5. It is apparent that at smaller radial distances, the stream's dispersion is radially dominated but rapidly decreases at further distances.

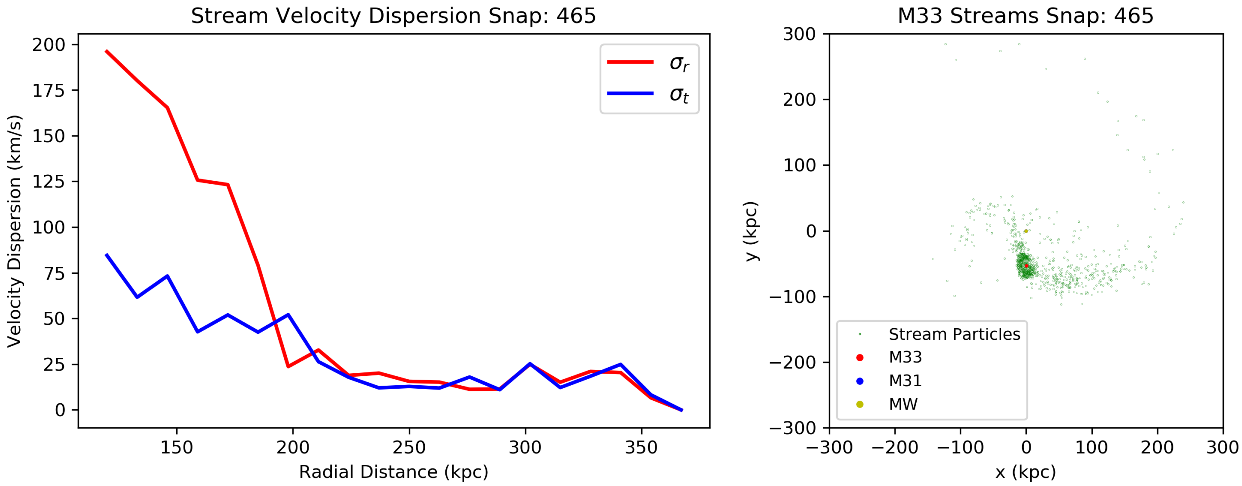

Figure 3. Left: radial (σ_r) and tangential (σ_t) velocity dispersion (y axis) in km/s plotted as a function of radial distance from M33's CoM (x axis) in kpc. σ_r/σ_t is ≈ 2.5 at small distances from M33. Right: X and Y positions in kpc of stream partilces (green), M33 (red), M31 (blue) and the MW (yellow) at snap shot 465. The leading tail is left of M33, and the trailing to the right. At this point in the simulation, the MW's CoM and M31's CoM are overlapping in the center of the plot. There is an obvious difference in the appearance of the leading and trailing tails.

Plotted on the right is M33's streams at Snap shot 465. This frame was chosen because of it clearly shows M33's leading and trailing stream tails to the left and right of M33's CoM. At this point, the value of M_h is the MW/M31 CoM (see Figure 5). There is a clear asymmetry between the leading and trailing tails.

Figure 4 can be used to address the extent to which the streams trace the orbit of M33. The black line traces the orbit of M33 over the course of the simulation. By comparing the orbit with the position of the tails at a given snap shot, this plot can show how well the tails trace its orbit. It is apparent that M33's orbit during the merger is complicated, and changes with the evolving CoM of the LG. Regardless, the discrepancy between the tail's position and its past orbit suggest that streams cannot be used to trace it's orbital history.

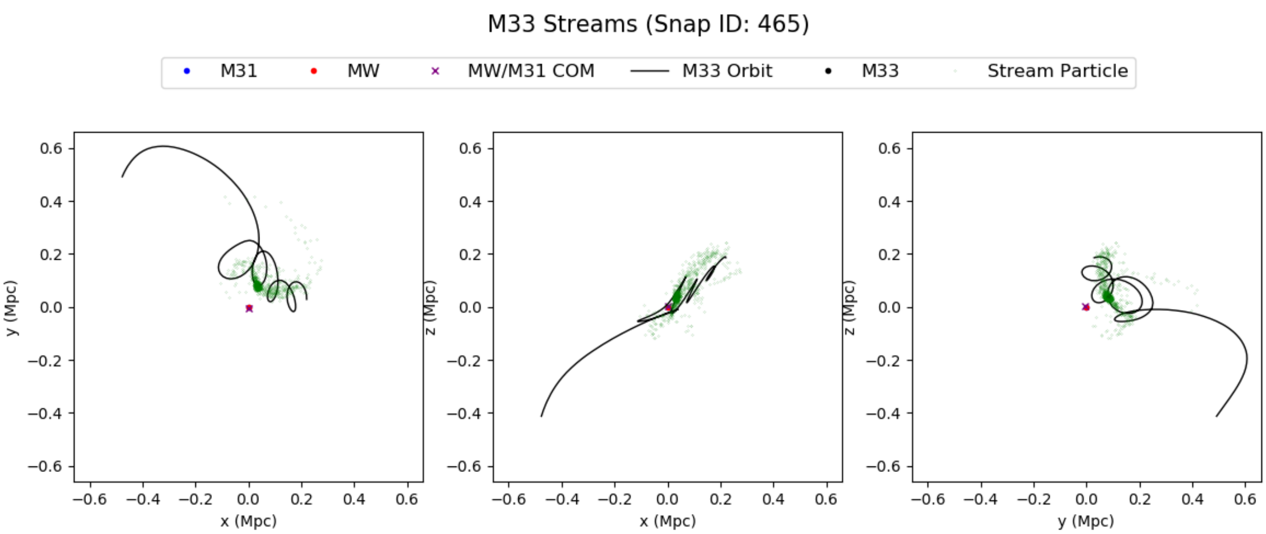

Figure 4. XY, XZ and YZ view of local group at snap shot 465. All axis are in Mpc. At this point, M31 (blue) and the MW (red) have merged, as indicated by their shared CoM (purple X) being at the center of the plot. The solid black line is M33's entire orbit over the merger, and the M33's position at the current snap shot is indicated by a black dot. Stream particles (green) swarm M33's CoM at this point.

5. DISCUSSION

The initial behavior of this plot supports the hypothesis suggested by (Amorisco 2016). M33, being a massive galaxy, does appear to contribute a radially biased stellar population to its stellar streams, however, there are differences in the trends presented in Figures 1 & 3. In Figure 1, σ_r and σ_t start at roughly the same value at small radii, but differ at larger radii. σ_r shows a gradual upward trend until around 11 kpc, at which point it decreases. σ_t stays constant until 5 kpc, and then rapidly decreases. In Figure 3, σ_r starts around 200 km/s, then rapidly decrease to the same value as σ_t around 200 kpc. Over this same interval, σ_t starts around 80 km/s, and decreases gradually. These differences could be indicative of the added dynamics of the on going MW and M31 merger while M33's stream form. This suggests that the added complications of a merger cannot be ignored in future studies of stream formation and evolution.

(Choi et al. 2007) claimed that streams are a poor tracer of a satellite's orbital history around its host. These claims are supported by Figure 4, which show a clear discrepancy between the position of M33's tails and it's past orbital history. When observing stellar streams around the MW and other galaxies, one might naively expect streams to reflect the past position of their progenitors. The results of both my study and (Choi et al. 2007) show that this cannot be assumed in studies of stellar streams, and a different mechanism should be used to trace satellite orbits around their host galaxies. Moreover, both Figures 3 and 4 show the broken stream symmetry discussed by (Choi et al. 2007). This result heavily favors their hypothesis for asymmetry, and indicates suggests that it holds even for satellite galaxies orbiting an ongoing merger.

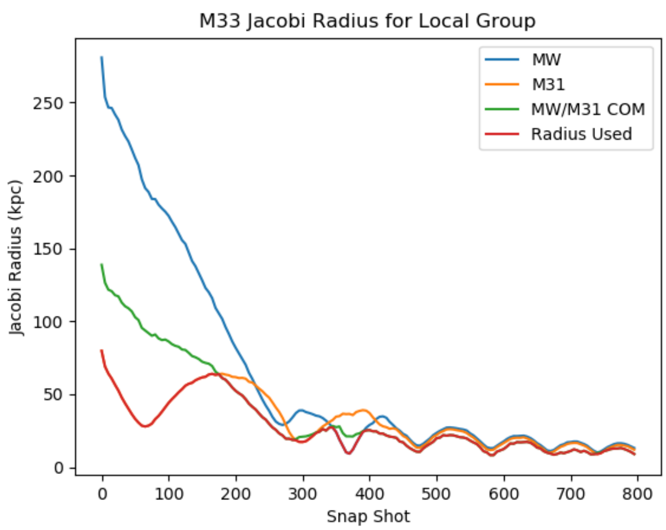

Figure 5. Jacobi radius of M33 in kpc (y-axis), calculated with different M_h, over the course of the simulation (x-axis). The M_h which produced the smallest R_j (indicated by the red line) was used to select stream particles.

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