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M33's Stellar Stream Kinematic Evolution during Milkdromeda Merger

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ABSTRACT

The gravitational interactions that occur during a galaxy merger have considerable consequences on the kinematics and disk structure of the system's satellite galaxies. This work will utilize data from the Milk Way-Andromeda collision simulation presented in (R. P. van der Marel et al. 2012), a collisionless N-body simulation that depicts the most likely fates of the Milky Way, Andromeda, and M33 galaxy local group system over the next few billion years. This data will allow us to look into the patterns and kinematic behavior of the stellar stream structures of a satellite galaxy around a merger. On average, the velocity magnitude of M33's leading stream through time is 265.56 km/s while the velocity magnitude of the trailing stream is 227.81 km/s, suggesting that leading stream velocities are about 1.17 times greater than those of the trailing stream. This alludes to a more energetic leading stream that will keep M33 gravitationally attracted to the merger and cause it to eventually merge with the Milky Way-Andromeda merger remnant. Characterizing the kinematic behavior of these streams as they interact with the larger merger can provide insights into how tidally disruptive processes impact a system's morphology and kinematics.

Keywords: Satellite Galaxy — Local Group — Jacobi Radius — Tidal Tails — Tidal Stripping — Velocity Dispersion — Galaxy Evolution

1. INTRODUCTION

The tidal stripping of stellar mass that occurs when a galaxy is being tidally disrupted often creates distinct stellar stream structures. In the case of a satellite galaxy whose host galaxy is merging with another, the satellite's tidal debris will be pulled towards the more massive merging system. The kinematics of these stellar streams are related to galaxy evolution, revealing how the evolutionary history of a satellite galaxy is impacted by dynamical interactions with the other galaxies in the system. The evolving dynamics of M33's stellar streams during the Milky Way-Andromeda (Milkdromeda) merger will be further studied in this work.

This topic is very important in understanding galaxy evolution because it helps contextualize how tidal disruptions in the form of stellar streams are created and evolved by kinematic interactions between galaxies. Studying the kinematic profiles of M33's stellar streams provides a better understanding of how a merger can impact the evolutionary history of a satellite galaxy (K. V. Johnston et al. 1999). A **galaxy** can be defined as "a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity.", which implies the necessary presence of a dark matter halo (B. Willman & J. Strader 2012). Correspondingly, **galaxy**

evolution refers to the way in which galaxy objects grow and change over time (B. Willman & J. Strader 2012). The leading theory on galaxy formation is described by the cold dark matter (CDM) cosmological model, which suggests that galaxies form through hierarchical merger events and accretion. The CDM model suggests that galaxies lie within dark matter halos that form through the accretion and disruption of low-mass subhalos. Therefore, it is very important to understand the dynamical mechanisms that govern the formation and evolution of tidal debris in the form of stellar streams. These are the products of the subhalo disruption processes believed to be responsible for galaxy formation (N. Shipp et al. 2023).

As disk stars become tidally unbound, two main streams of tidal debris will form due to gravitational forces and the galaxy's own rotational motion. These are known as the **leading stream** (debris pulled towards host) and the **trailing stream** (lags behind the satellite). Each stream will experience different gravitational forces, causing them to have different velocity and kinetic energy distributions. Fig. 1 shows the leading and trailing streams of M33 (Andromeda's satellite galaxy) as they form from tidal disruptions caused by its proximity to Andromeda (M31).

Some of the open questions that exist within this topic include how the dark matter halo structure of the merger system relates to the satellite's stellar stream morphology. The role these stellar streams play in accretion events is also uncertain(K. Malhan et al. 2018). More research is also being done to better understand the physics behind predicting stellar stream patterns and kinematic behavior (V. P. Reshetnikov & N. Y. Sotnikova 2001).

2. THIS PROJECT

In this work, the differences in the kinematic evolution of M33's leading and trailing streams will be evaluated throughout the Milkdromeda merger. We will take a closer look at how the disk stars' velocities change before, during, and after the merger. Stars along each of the tidal streams will be selected to provide a direct comparison of their kinematic properties.

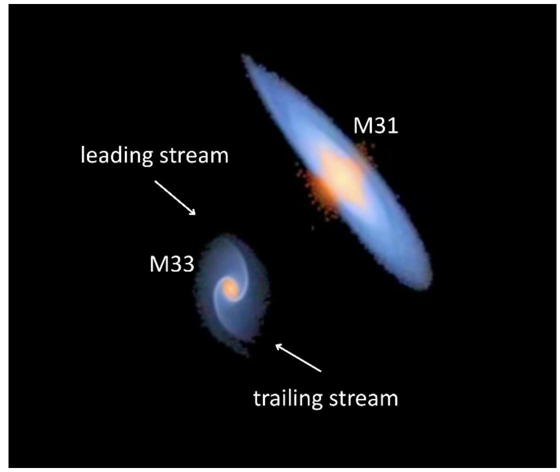

Figure 1. Simulation model showing M33's leading and trailing tidal debris streams. Model from N-body simulation created from Pan-Andromeda Archaeological Survey data (A. W. McConnachie et al. 2018).Not to scale.

This work will attempt to provide more context towards understanding the patterns and kinematic behavior of stellar stream structures on a satellite of a merger system. Attention will be directed towards addressing the differences in how the two major stream structures evolve throughout the merger.

Having a better understanding of these structures' kinematics is very important in the context of the CDM cosmological model. Being able to characterize stellar streams allows us to consider their role in galaxy formation and evolution theories.

3. METHODOLOGY

This work is based on the simulation data for the Milkdromeda collision presented in (R. P. van der Marel et al. 2012), which depicts the most likely fates of the Milky Way, Andromeda, and M33 galaxy local group system over the next few billion years. This is a collisionless

N-body simulation that predicts the behaviors of any given large number of particles (N) with some attributed mass in the system. The initial parameters used in the simulation and the number of particles in each galaxy component (halo, disk, and bulge) are defined in Table 1 of (R. P. van der Marel et al. 2012).

The high-resolution simulation data is used in this work to study the fine structures of M33's stellar streams. All plots and analysis in this work will solely consider disk particles, not taking into account how M33's halo behaves throughout the merger. This data allows us to better visualize the two major stellar stream structures that form as M33 is tidally disrupted during the Milkdromeda merger (see Fig. 2).

In order to examine M33's evolving streams, particles that make up those streams must are selected for through computing the Jacobi radius of the galaxy. By definition, particles that are at or beyond the **Jacobi radius** will no longer be gravitationally bound to M33 (J. I. Read et al. 2005). The Jacobi radius of M33 is computed as stated in Eq. 1.

$$R_j = r\left(\frac{M_{sat}}{2M_{host}(< r)}\right)^{1/3} \tag{1}$$

where R_j is the Jacobi radius, r is the distance from one galaxy's center of mass to the other's, M_{sat} is the mass of the satellite galaxy, and M_{host}(¡r) is the mass of the host galaxy within the distance between the two

The difference in each stream's kinematics will be analyzed by using velocity as a proxy for kinetic energy due to the relationship stated in Eq. 2. Furthermore, the formation and evolution of M33's stellar streams can be contextualized by the gravitational or tidal force that causes these tidal disruptions as expressed in Eq. 3.

$$KE = \frac{1}{2}mv^2 \tag{2}$$

where KE is the kinetic energy, m is the mass of the stream, and v is the velocity magnitude of the stream

$$F_{tide} = \frac{GMm}{r^2} \tag{3}$$

where F_{tide} is the tidal force experienced by two gravitationally interacting bodies, G is gravitational constant, M is the mass of the host galaxy, m is the mass of the satellite galaxy, and r is the distance from one galaxy's center of mass to the other's

In addition to the velocity dispersion plots showing how M33's streams evolve through time with velocity magnitude color coding, a plot of average stream particle velocity over time will also be created. This plot will show the difference in average velocities of the leading and trailing streams throughout the merger. Particles at different radii along the streams are selected to find the average velocity of each of them. A Jacobi radius over time plot will also be created to help us visualize how M33's orbital stages impact its stellar streams. Although this work will not discuss mass loss rates, the effects of mass loss due to the tidal stripping that M33 will experience is reflected through the changing Jacobi radius and average stream particle velocity.

From the plots produced in this work, I expect to see the velocity of all stellar stream particles increase with time as M33 is gravitationally pulled towards the Milky Way-M31 merger. The velocity values are expected to change during close encounters with the Milky Way-M31 merger as particle velocity and momentum distributions are rearranged throughout the system. As for the kinematic differences within each stream, the leading stream will likely have higher average velocities as it is gravitationally pulled towards M31 with stronger tidal forces than those acting on the trailing streams because tidal force is proportional to the inverse

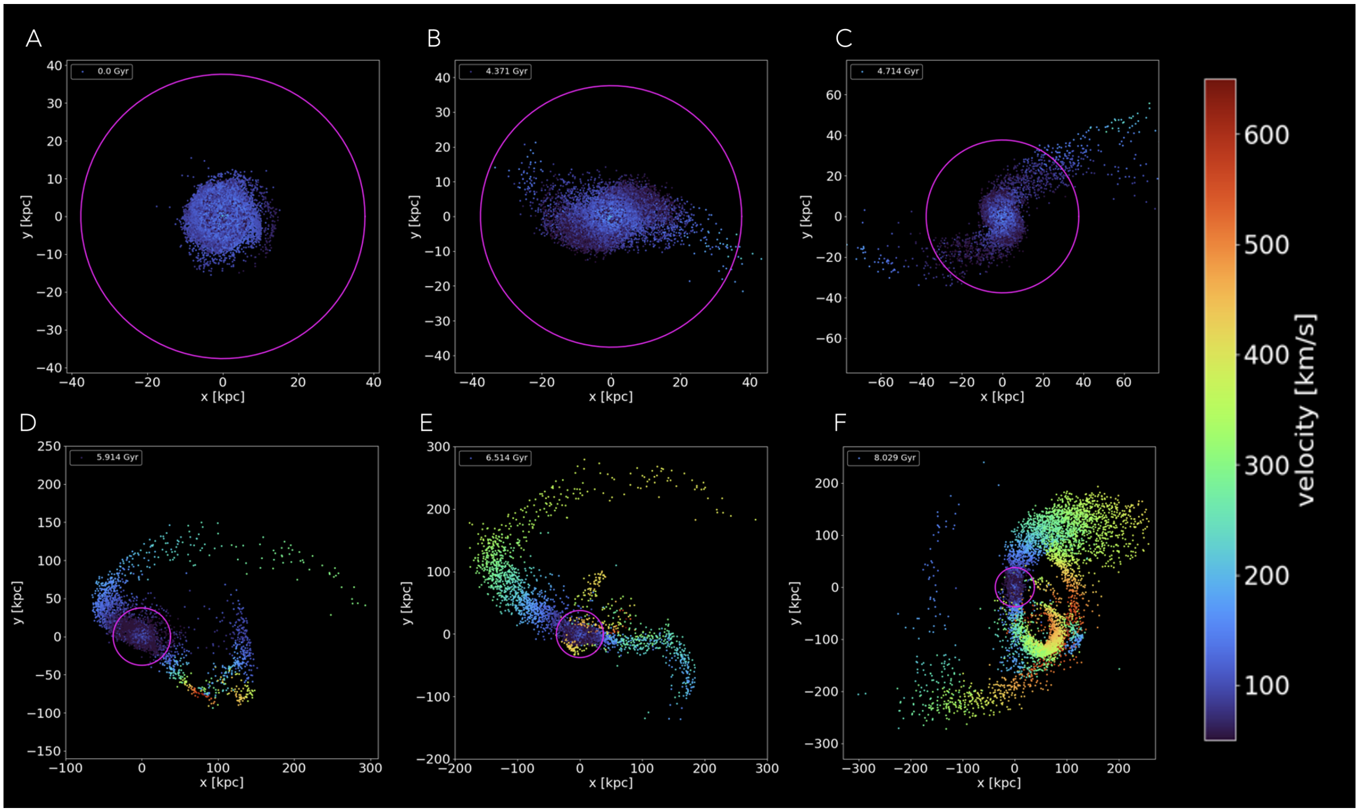

Figure 2. Plots of M33 disk particles color coded by velocity magnitude during significant stages of the Milky Way-Andromeda merger; showing magenta circle of radius = Jacobi radius, and corresponding timestamp in the legend. A) M33 at the present day, B) M33 during the Milky Way and Andromeda's first close encounter C) M33 after first Milky Way and Andromeda close encounter, D) M33 during the Milky Way and Andromeda's second close encounter, E) M33 when the Milky Way and Andromeda merge, F) M33 after only merger remnant remains. These plots help visualize the velocity gradients of each stream through time.

of the distance square. Since the leading stream stays closer to the host, it will likely have higher velocities and kinetic energy compared to the trailing stream.

4. RESULTS

The Jacobi radius determines which stars become unbound to M33 and go on to become part of the tidal debris streams. The equation for the Jacobi radius of M33 (Eq. 1) suggests it will change based on the distance between the centers of M33 and M31, as well as the mass of M31 within that distance. The Jacobi radius is then found to increase when M33 gets closer to M31 (at its orbit's pericenter), and will decrease when M33 gets further from M31 (at its orbit's apocenter). This variation in M33's Jacobi radius over time is shown in Fig. 3. This figure also shows how the Jacobi radius at M33's pericenter is much larger before the Milky Way-M31 merger ($t< 6.5$ Gyr) than after the merger ($t > 6.5$ Gyr). This is due to M31's mass loss as it merges with the Milky Way.

The average velocity magnitudes of both leading and trailing streams over time are plotted in Fig. 4. The black solid line represents the leading stream average velocities, while the dashed magenta line represents the trailing stream average velocities through time. The average particle velocity magnitude of the leading stream through time is 265.56 km/s, while the average particle velocity magnitude of the trailing stream through time is 227.81 km/s. This plot also shows both stream velocities peak around 5.5 Gyr and 7.5 Gyr, which corresponds to M33 being at pericenter.

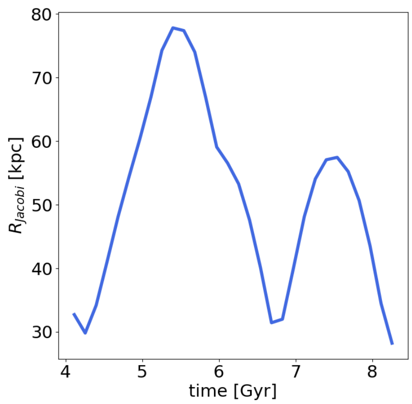

Figure 3. Plot of M33's Jacobi radius over time. Peaks at pericenter and minimum at apocenter, second peak is smaller due to host mass loss during the merger.

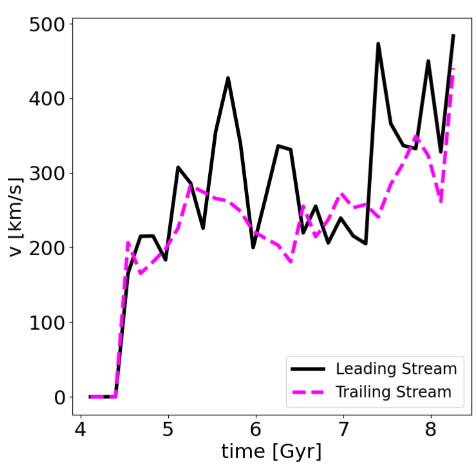

Figure 4. Plot of the average velocity of leading and trailing stream particles over time. The leading stream has an average velocity of 265.56 km/s while the trailing stream has an average velocity of 227.81 km/s over the course of the Milky Way-M31 merger.

5. DISCUSSION

The magnitude of stellar stream velocities over time are shown to increase with time as shown in Fig. 4. This plot reveals that the leading arm velocities are on average 1.17 times greater than the trailing arm velocities. This result is as predicted in my hypothesis, where the leading arm has higher velocities because it is gravitationally pulled towards M31 as it merges with the Milky Way. The argument of both streams having increasing velocities through time also aligns with my hypothesis as M33 is gravitationally pulled towards the merger.

These results correlate to the findings of other papers on stellar stream kinematics, such as (J. I. Read et al. 2005) and (G. Kang et al. 2023). The leading stream is shown to have higher velocities on average than the trailing stream, thus higher kinetic energy as discussed in (R. A. N. Brooks et al. 2024). The leading stream gains energy due to its proximity to the host galaxy, while the trailing stream loses energy as it lags behind the galaxy and experiences dynamical friction. This kinematic behavior tells us about the expected dynamical interactions between tidally disrupted satellites around a large merger. This increase in velocity over time suggests that the satellite galaxy – M33 in this case– will likely lose mass to its host galaxy's merger and eventually merge with the remnant as it is gravitationally pulled towards it. The tidal disruptions that lead to this behavior are extremely important in galaxy evolution, as they are able to completely transform the galaxies' star formation and structure.

The dynamical behavior of M33's stellar streams studied in this work has uncertainties stemming from the lack of consideration for the Milky Way's direct contributions. The assumption that the Milky Way and Andromeda will interact with each other so strongly during the merger that the impacts on M33 can be found from considering M31 alone neglects added factors to these physical interactions. The effects of the Millky Way on M33 during the merger will undoubtedly change the kinematic trends found in this work.

6. CONCLUSION

The gravitational interactions that occur during a galaxy merger have considerable consequences on the kinematics and disk structure of the system's satellite galaxies. This work will utilize data from the Milk Way-Andromeda collision simulation presented in (R. P. van der Marel et al. 2012), a collisionless N-body simulation that depicts the most likely fates of the Milky Way, Andromeda, and M33 galaxy local group system over the next few billion years. This data will allow us to look into the patterns and kinematic behavior of the stellar stream structures of a satellite galaxy around a merger. On average, the velocity magnitude of M33's leading stream through time is 265.56 km/s while the velocity magnitude of the trailing stream is 227.81 km/s, suggesting that leading stream velocities are about 1.17 times greater than those of the trailing stream.

The kinematic evolution of M33's stellar streams supports the hierarchical nature of galaxy formation described by the CDM cosmological model, predicting the result of a new system formed from the remnant of this system's merger events. These results build off the tidal and rotational processes that govern how satellite galaxies normally interact with their host, but considering the instabilities that the host now being a merging system of two massive galaxies brings. This agrees with my hypothesis, since it all follows the same general physical intuition about how shifts in the gravitational forces experienced between two objects will often cause these drastic changes in the system.

To further explore how these tidal disruption processes contribute to galaxy formation according to the CDM cosmological model, the dark-matter halo evolution must be accounted for. Seeing if the predicted overdensities occur as the halo is shaped along with the evolving streams would provide more evidence for the hierarchical behavior of theorized galaxy formation models. To improve my analysis of the streams' evolution, I could have plotted circular velocities instead of velocity magnitudes to provide more context on the particles' distribution. The analysis of the streams' kinematic evolution during the merger could have also focused more on how dynamical friction is manifested in this work's findings. The dynamical friction experienced in this process was not directly calculated, but its role in slowing down the trailing stream was recognized.

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