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M33's Stellar Stream Kinematic Evolution during Milkdromeda Merger

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ABSTRACT

This is the abstract...for now...

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. Tidal streams and stellar streams will be used interchangeably throughout this work. 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 also 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 throughout the Milkdromeda –Milky Way and Andromeda– 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.

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). Fig. 1 shows the streams of a low-mass satellite simulated with gravitational acceleration (right panel) and without gravitational acceleration (left panel), which shows how certain dynamical mechanisms can impact stellar stream density and kinematic profiles.

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).

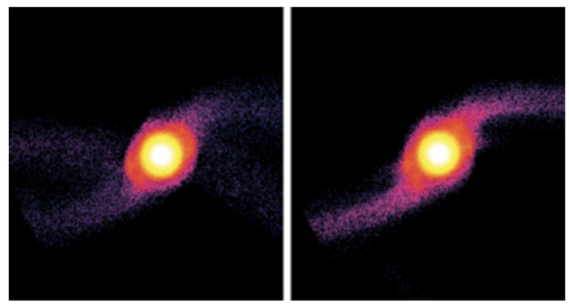

Figure 1. Streams of a low-mass satellite simulated with gravitational acceleration (right panel) and without gravitational acceleration (left panel)(J. Choi et al. 2007). These plots are color coded by particle density and demonstrate how changes in kinematic conditions lead to different stream structures.

2. THIS PROJECT

In this work, we will study the dynamics of M33's tidal streams throughout the Milkdromeda merger. We will take a closer look at how the disk stars' velocities change before, during, and after the merger. Stars in the tidal streams will be selected for this analysis.

This work will try to provide more context towards understanding the patterns and kinematic behavior of stellar stream structures on a satellite of a merger system.

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 unconventional star formation and galaxy evolution theories.

3. METHODOLOGY

This work will be based off 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 system over the next few gigayears. 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).

In order to study the fine structures of M33's stellar streams, the high-resolution simulation data must be used. All plots and analysis in this work will solely consider disk particles, not taking into account how M33's halo behaves and interacts with the system throughout the merger (see Fig. 2).

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

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

where R_j is the Jacobi radius, r is the ditance 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 relation stated in Eq. 2. Furthermore, the formation and evolution of M33's stellar streams can be contextualized by the gravitational 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 over time with velocity magnitude color coding, a plot of average stream particle velocity over time will also be created. A Jacobi radius over time plot will also be created to help us visualize what main parameters are changing throughout the merger.

Although this work will not discuss mass loss rates, the effects of mass loss due to the tidal stripping that M33 will experience will be 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 stellar stream particles increase with time as M33 is gravitationally pulled towards the MW-M31 merger. The velocity values are expected to change during close encounters with the MW-M31 merger as particle and momentum distributions are rearranged throughout the system.

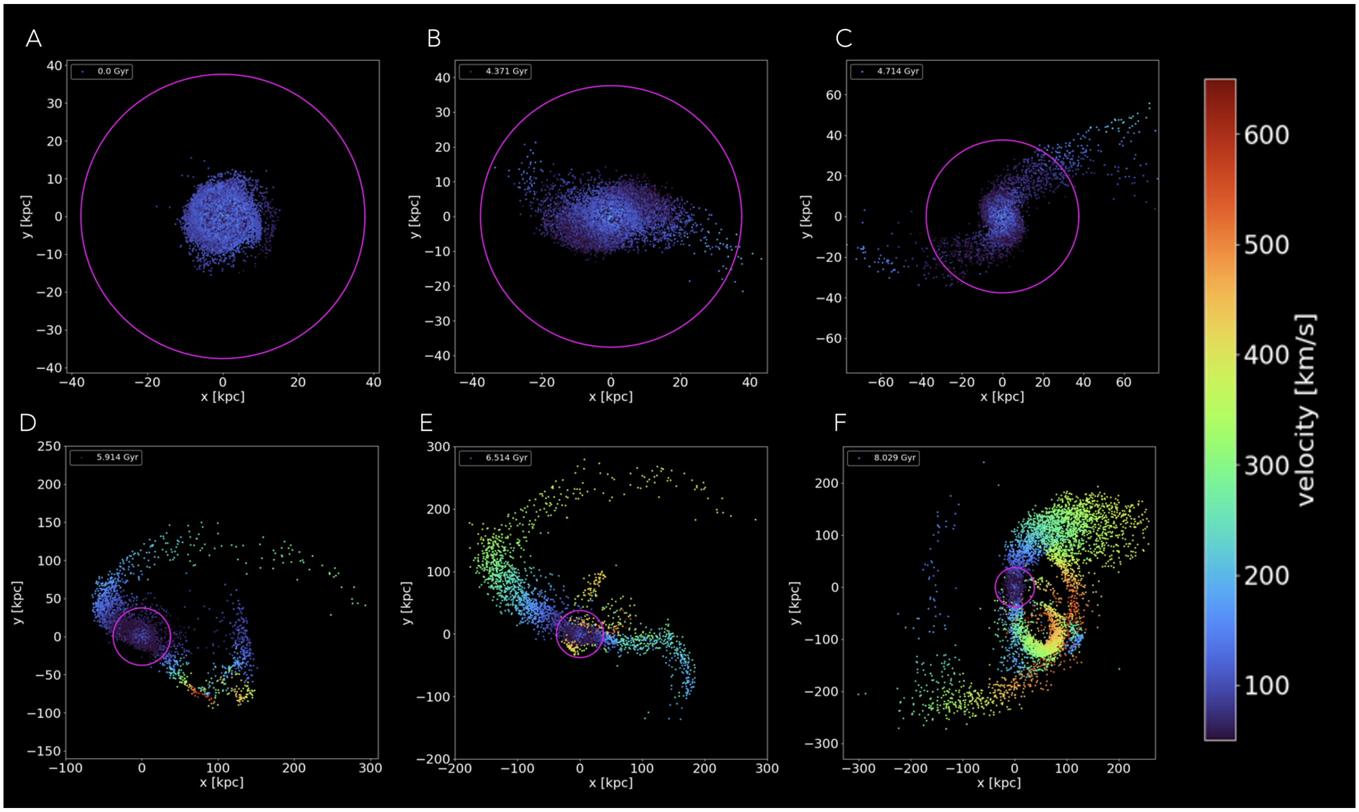

Figure 2. Plots of M33 disk particles color coded by velocity magnitude during significant stages of the Milky Way-Andromeda merger showing magenta circle of radius = Jacobi radius. A) M33 at the present day, B) M33 during the Milky Way and Andromeda's first close encounter C) M33 after first Milky Way and Andromeda close encounter, D) M33 during 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 suggest dynamically active tidal streams and tidal stripping in M33's disk during the Milkdromeda merger.

4. RESULTS

The Jacobi radius determines which stars become unbound to M33 and go on to becoming 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 is closer to M31 (at its orbit's pericenter), and will decrease when M33 is further from M31 (at its orbit's apocenter). This variation in M33's Jacobi radius over time is shown in Figure 3. This figure also shows how the Jacobi radius at M33's pericenter is much larger before the MW-M31 meger (t¡6.5 Gyr) than that after the merger (t¿6.5 Gyr). This is due to M31's mass loss due to it merging with MW.

As M33's stars become tidally unbound, two main streams of tidal debris will form. These are known as the leading stream (is pulled towards host and usually shorter) and the trailing stream (lags behind and usually longer). This is confirmed in the case of M33's streams as seen in Figure 4. These results reveal that the leading arm velocities are on average 1.17 times greater than the trailing arm. This figure also reveals how the velocity of both streams peak at around 5.5 Gyr and 7.5 Gyr, which correspond to M33 being at pericenter. This kinematic behavior is as expected, since particles

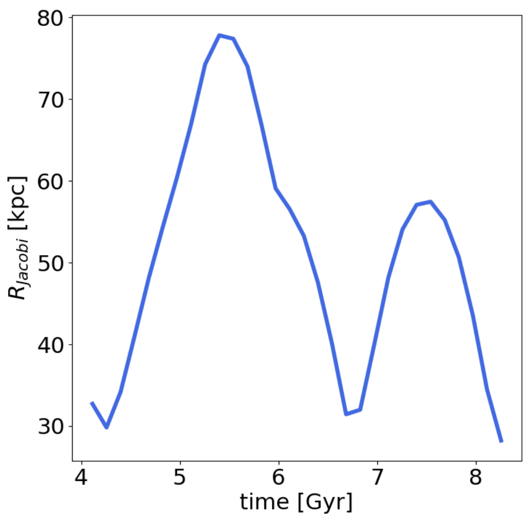

Figure 3. Plot of the Jacobi radius over time.

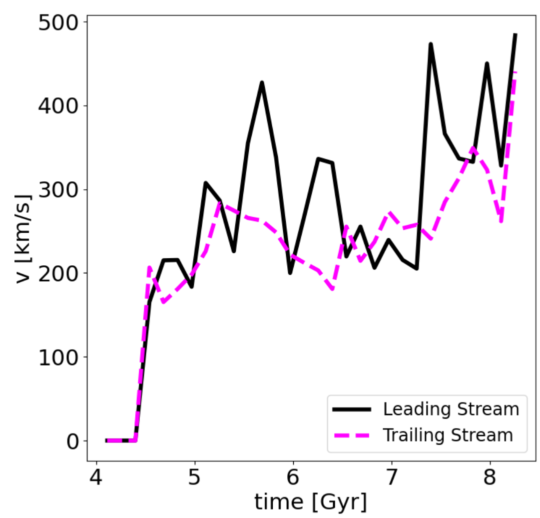

Figure 4. Plot of the average velocity of leading stream particles and trailing stream particles over time. Leading stream has an average velocity of 265.56 km/s while the trailing stream has an average velocity of 227.81 km/s over the course of the MW-M31 merger.

will be gravitationally accelerated when getting closer to M31. This trend is also seen as the velocity magnitudes of both streams increase with time after the MW-M31 merger occurs because M33 is gravitationally accelerated towards the massive merger.

5. DISCUSSION

The magnitude of stellar stream velocities over time are shown to increase with time as shown in Figure 4. This result is as predicted in my hypothesis about velocities increasing as M33 is gravitationally pulled towards the M31-MW merger.

These results correlate with 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 energies as discussed in (R. A. N. Brooks et al. 2024). Where the leading stream gains energy due to its proximity to the host galaxy, while the trailing stream losses energy as it lags behind the galaxy. This kinematic behaviors tells us about the expected dynamics between tidally disrupted satellites around a merger between two massive galaxies. This increase in velocity over time suggests that the satellite galaxies – M33 in this case– will likely loss 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 Andromeda alone as M33's host does neglect some minor physical interactions. The effects of MW on M33 during the merger will undoudetly change kinematic trends found in this work slightly.

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