Velocity Dispersion of Disk Particles in Tidal Tails formed by the Milky Way-M31 Merger

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1 INTRODUCTION

Studying the evolution of galactic **tidal tails** is essential to gain a better understanding of **major mergers**. Tidal tails are the result of gravitational interactions between galaxies. During the interaction, stars and gas get pulled away from the **stellar disks**, or outer regions, of the galaxies due to tidal forces. These features can stretch for over hundreds of kiloparsecs and can persist for a few billion years. The tidal tails that link the perturbing galaxy to the perturber are known as **tidal bridges**. Tidal bridges and tails are considered a signature of a recent major merger. Major mergers play a role in galactic morphological transformations, as well as trigger bursts of star formation and redistribute material. These tidal tails and bridges also serve as crucial observational evidence for the **hierarchical growth** model of galaxies, which suggests that galaxies form through a series of mergers and other accretion events. Understanding the formation and persistence of these tidal features is crucial to unraveling the physical processes that govern galaxy growth and evolution.

Studying tidal tails and tidal bridges aids in understanding galactic evolution because these processes reveal the interaction history between galaxies. A **galaxy** is a gravitationally bound system of stars whose properties cannot be explained by a combination of baryons (gas, dust, and stars), and Newton's laws of gravity. **Galaxy evolution** refers to the processes by which galaxies form, grow, interact, and change in structure and composition over time. The presence of tidal tails and bridges can be observed to better understand how they contribute to morphological transformations of galaxies. Tidal debris also serve as a visible record of past mergers, providing astronomers with evidence of gravitational encounters that occurred billions of years ago. Analyzing the distribution, kinematics, and composition of tidal debris can inform models of how galaxies grow, evolve, and even trigger new star formation. Tidal tails and bridges can also serve as dynamical markers of the dark matter halo structure, and also provide a framework for how galaxies continue to evolve in different environments, from isolated pairs to dense galaxy clusters.

Tidal tails and bridges are formed from gravitational physics. These interactions come into play during close encounters of galaxies. Each encounter is considered to involve only two galaxies. The tidal forces that act on spiral galaxies during a close encounter, as well as their rotational motion, draw out long tails of gas of stars. For the first passage, tidal forces give the disks enough energy to escape the inner potential well.Mihos (2004) After this near direct passage of the companion galaxy, the outer portions of the disk will deform into a spiral arm that connects the two galaxies, called a bridge. A counterarm will also form on the far side of each galaxy, forming
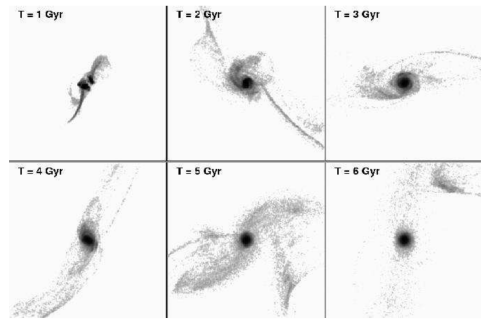
Figure 1. Evolution of an equal-mass merger. Note the rapid stripping of the tidal tails early in the simulation; the tidal debris seen here is more extended and diffuse than in the field merger, and late infall is shut off due to tidal stripping by the cluster potential. (Figure 3, Mihos (2004))

the tail. This occurs due to the symmetric nature of tidal forces. If the partner galaxy is equal in mass or more massive, then a tail of escaped debris forms from the perturbed disk. In addition, disk particles from the near side get swept into the perturber galaxy. Toomre & Toomre (1972) Tidal tail formation is strongly correlated to orbital geometry. Mihos (2004) They are strongest in prograde encounters, where spin and angular momentum vectors are aligned to a moderate extent. The tails are weakest in a retrograde encounter. Due to the pair of galaxies' orbital decay, these can cause the galaxies to fall away from their tails as they merge together. Tidal tails change as time passes. Most of the material remains bound to the remnant within loose elliptical orbits. Over billions of years, some of the tidal tail material at the base will fall back into the merger remnant, and the outer portions will continue to expand. This will result in continual stretching of the tidal tail. Mihos (2004)

When making N-body simulations of tidal tail formation and evolution from mergers, the test-particle method is a way to explore and understand kinematics and morphology of interacting galaxies. One example software this is done with is called Identikit, used thoroughly for simulating mergers. Dynamical models were simulated using this software and detailed in a paper authored by Privon et al, in 2013. Within the paper, they were only to simulate a few known mergers that were observed by space telescopes. From their paper, the only parameter which showed a noticeable bias in the best fit values compared to the true values was the velocity scaling. However, it was stated that it could be easily explained by the lack of velocity dispersion in the test-particle method. The test-particle disks that they used

had zero velocity dispersion, which were used to match tails formed from disks with a non-zero velocity dispersion. The velocity scaling determined by test-particle matching would thus have to be inflated in order to compensate for this. Privon et al. (2013) The solution to this discrepancy lies in using test-particle models that can include or calculate velocity dispersion. In reality, particles experience velocity dispersion as they are subject to mergers. In the disk of a galaxy, the dispersion is low, as stars make up a majority of the disk, and follow circular orbits around the galactic center. When the merger occurs, the velocity dispersion increases, especially in tidal tails.

2 THIS PROJECT

In this paper, we will study the formation and evolution of tidal tails that occur during the Milky Way–M31 merger. These structures can provide insight into redistribution of mass and angular momentum during a major merger. Using N-body simulation data, we will track the development of these tidal features throughout different stages of the merger. In addition, we will calculate and analyze the change in velocity dispersion of disk particles over time, with a focus on how the kinematic properties of the stellar disks are altered by tidal forces. By plotting the evolution of velocity dispersion across multiple time steps, we aim to better understand the dynamical impact of the merger on the structure of the resulting remnant elliptical galaxy.

This project addresses the limitations highlighted in the Privon et al. (2013) paper with regard to the lack of velocity dispersion in the test-particle models. Their findings pointed out a bias in velocity scaling when using test-particle disks with zero velocity dispersion to model systems where dispersion is actually non-zero. By focusing on the change in velocity dispersion during the Milky Way–M31 merger, this project will explore how velocity dispersion evolves dynamically, rather than assuming a static or negligible value for the test particles.

This project will allow for investigation into how dispersion impacts tidal tail morphology and kinematics using a more realistic set of test-particle data. Velocity dispersion plays a key role in determining the structural and kinematic properties of galaxies. If simulations neglect or oversimplify the impact of velocity dispersion, they risk misrepresenting the true dynamical state of merging systems. This is particularly true in tidal tails, where dispersion increases significantly. By quantifying how velocity dispersion changes over time during the Milky Way–M31 merger, this study provides a more physically realistic perspective on the dynamics of merging disks.

3 METHODOLOGY

In this project, N-body simulations based on the merger models presented in van der Marel, Besla et al. (2012, *ApJ*, 753, 9), will be utilized. An N-body simulation is a numerical technique used to study gravitational interaction of a system of particles, where each particle represents a portion of mass—such as stars, gas, or dark matter—in the galaxy. These simulations allow for tracking of the dynamical evolution of galaxies by solving Newton's laws of motion and gravity for all particles simultaneously. In the van der Marel & Besla model, each galaxy is initially represented by a combination of a dark matter halo and a stellar disk. The dark matter halos follow a Navarro-Frenk-White (NFW) density profile, which is used in cosmological simulations to model the structure of halos formed through hierarchical clustering. The stellar disks are embedded within these halos and are modeled as rotationally
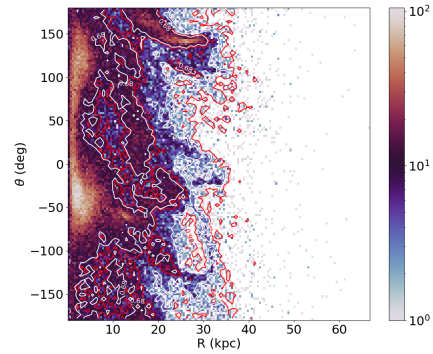
Figure 2. A phase diagram of a snapshot of M31 disk particle data. This is from the Lab 7 in-class assignment. Note the arm on the top of the paper; the outstretched material is considered to be prominent tidal debris.

supported components with an exponential surface density profile. These initial conditions provide a realistic framework for analyzing the complex gravitational dynamics of the Milky Way–M31 merger, including the formation of tidal features over time.

This study will use the HighRes version of the Milky Way–M31 merger simulation data. This was chosen because the high resolution data provides the spatial and mass resolution essential for capturing interaction dynamics. The analysis focuses on disk particles from both the Milky Way and M31, as these represent the part of the galaxy that is most directly affected by tidal interactions. Using methods adapted from previous coursework, we compute the center of mass (COM) positions and velocities of each galaxy to shift into a COM frame for kinematic analysis. To identify tidal tails, phase diagrams (theta vs. radius) will be generated to detect kinematic outliers that lie far from the main rotation curve at large radii. After identifying the tidal tail particles, their time evolution can be tracked across a series of snapshots, preserving their indices to monitor changes in both spatial configuration and velocity dispersion. This approach enables for investigation of the evolution and progression of tidal tails as the merger progresses.

The core calculations in this project involve determining the positions and velocities of disk particles relative to their host galaxy's center of mass, as well as tracking the evolution of velocity dispersion in the tidal tails over time. To analyze the structure and kinematics of each galaxy, we first shift into a center-of-mass (COM) frame, computing both the position and velocity of the stellar disk relative to the COM using the methods developed in prior coursework. The total spatial separation of each particle from the galaxy center is calculated using the Euclidean distance formula:

$$r = \sqrt{(x - x_{COM})^2 + (y - y_{COM})^2 + (z - z_{COM})^2} \tag{1}$$

where x, y, and z are the particle's coordinates and x_{COM}, y_{COM} and z_{COM} are the coordinates of the galaxy's center of mass.

The total velocity relative to the galaxy's bulk motion is computed as:

$$v = \sqrt{(v_x - v_{x,COM})^2 + (v_y - v_{y,COM})^2 + (v_z - v_{z,COM})^2} \tag{2}$$

where v_x, v_y, and v_z are the particle's velocity components and

$v_{x,COM}$, $v_{y,COM}$, and $v_{z,COM}$ are the velocity components of the galaxy's COM.

To identify tidal tails, phase diagrams will be made by plotting particle velocities against their galactocentric radii. Particles that significantly deviate from the expected rotation curve—particularly those with large velocities and/or located at large radii—are flagged as outliers and are interpreted as likely members of the tidal tails. For reference, the circular velocity of disk particles can be estimated using:

$$V_c = \sqrt{\frac{GM(r)}{r}} \tag{3}$$

where G is the universal gravitational constant, M(r) is the enclosed mass at radius r, and V_c is the circular velocity.

After selecting tidal tail particles based on their phase-space positions, we track them across simulation snapshots using their unique particle IDs and compute the velocity dispersion at each time step:

$$\sigma^2 = \frac{1}{N}\Sigma(v_i - \bar{v})^2 \tag{4}$$

where v_i are individual particle velocities, $\bar{v}$ is the mean velocity of the group, and N is the number of particles in the tail. This allows us to track the particles in the tidal structures across snapshots and better understand how the merger affects their internal kinematics.

To investigate how tidal tails evolve during the Milky Way–M31 merger and how their velocity dispersion changes over time, two types of plots will be generated. The first is a phase diagram (theta vs. radius) for disk particles in both galaxies. This type of plot was developed in Lab 7, and will help identify outlier particles that do not follow the main disk rotation curve. The second plot will be a time evolution figure of velocity dispersion for tidal tail particles identified after the first encounter. This figure will be generated using a function that tracks the same set of disk particle indices across successive snapshots and calculates their velocity dispersion at each time step. The plot will display velocity dispersion versus time. and will allow me to test the hypothesis that tidal tails gain internal velocity spread as a result of repeated gravitational interactions. Together, these two plots will answer my core research question by showing both the *structure* of the tidal tails (via phase space) and the *dynamical evolution* of their kinematics (via dispersion growth).

The hypothesis for this project is that tidal tails gain internal velocity spread as a result of repeated gravitational interactions. Tidal bridges will not have as much velocity spread. This prediction is motivated by the expectation that repeated gravitational encounters and tidal stripping events will dynamically heat the outer regions of each galaxy's disk. As stars are pulled into extended tails, they become more susceptible to gravitational forces that are not only from the interaction with the companion galaxy but also from the evolving potential of the system as a whole. Unlike the inner disk, where stars follow relatively ordered, circular orbits, stars in the tails are no longer bound in a coherent structure and are more likely to exhibit random motions. This should manifest itself as a rise in velocity dispersion. Observing an increase in dispersion over time would allow for a better understanding on their formation and evolution throughout a major merger.

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