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Charting M33's Stellar Stream Dynamics Following The Milky Way-M31 Merger

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1. INTRODUCTION

For the most prominent model on how galaxies evolve, the standard ΛCDM cosmology, galaxies follow a model of **hierarchical growth** and evolve via a series of mergers with neighboring smaller star systems (K. V. Johnston et al. 2008), mostly via a process called **tidal stripping**, through which more massive galaxies strip smaller objects from stars and other materials by strong tidal forces. One of the predicted resulting factors in these mergers are coherent streams of stars that are stripped from their original host by the stronger tidal forces from the larger galaxy (J. Jensen et al. 2021). Contrary to **tidal tails**, which are broad arcing arms of stars and gas, stellar streams are much narrower and are composed mostly of stars, resulting from a gradual disruption. As such, the existence of such streams hints at the scenario in which galaxies evolve via merging, and the dynamics of such objects may reveal crucial information on the history of a given galaxy.

Considering the distance these streams generally are from the galactic center, their dynamical timescales are much longer, which allows us to peer into past conditions of this system, forming something akin to a "fossil record" for past mergers of a specific galaxy (K. V. Johnston et al. 1996). Thus, studying these streams' dynamics is deeply beneficial to understanding how galaxies evolve and can even provide insight on how different kinds of mergers affect the resulting galaxy, strengthening or weakening the ΛCDM framework. Furthermore, it has been discussed that measuring the amounts of stellar streams a galaxy has can put a lower limit to past merging events and also present indirect evidence for the existence of dark matter sub-haloes (K. Malhan et al. 2018).

At this point in time, as J. Jensen et al. (2021) evidences, we are getting access to revolutionary amounts of observational data concerning galactic structures, which includes cataloging Milky Way's stellar streams (Figure 1). This revolution also comes in the form of deeply detailed simulations aiming at describing the behaviors of such streams and justifying the observations we are gathering (J.-H. Choi et al. 2007).

Despite the enormous advances and breakthroughs seen in recent years, big questions remain. Some depend only on our advancing observational technology, such as what the total quantity of stellar streams would be for our own galaxy, as even at this point some remain to be found (N. Shipp et al. 2023). Others that, even with technological advancements, may still be impossible to answer completely, such as what the nature of Dark Matter is or how galaxies are created and evolve in a more detailed frame, given the presence of highly stochastic processes (N. C. Amorisco 2017). However, the most pressing ones for this subject relate to how the kinematics are in these streams and the process through which they end up being accreted and have their mass assimilated by more massive galaxies, making them evolve. Answering these may result in a massive jump in how well we understand stellar streams and their broader impacts on galaxy evolution.

2. PROPOSAL

The aim within this project is going to be to better describe the stellar streams that will originate from a **satellite galaxy**, a smaller galaxy that is bound to a larger and brighter one, throughout a major merging event. More specifically we will be looking at particle simulations of M33 during the Milky Way-M31 merger. I will be looking especially at the dynamic properties of such an event, including velocity gradients and dispersion in the stream and how they evolve with time. My final goal is to answer how these kinematics evolve throughout the merging process and whether or not we can draw any conclusions from its behavior that may advance current research.

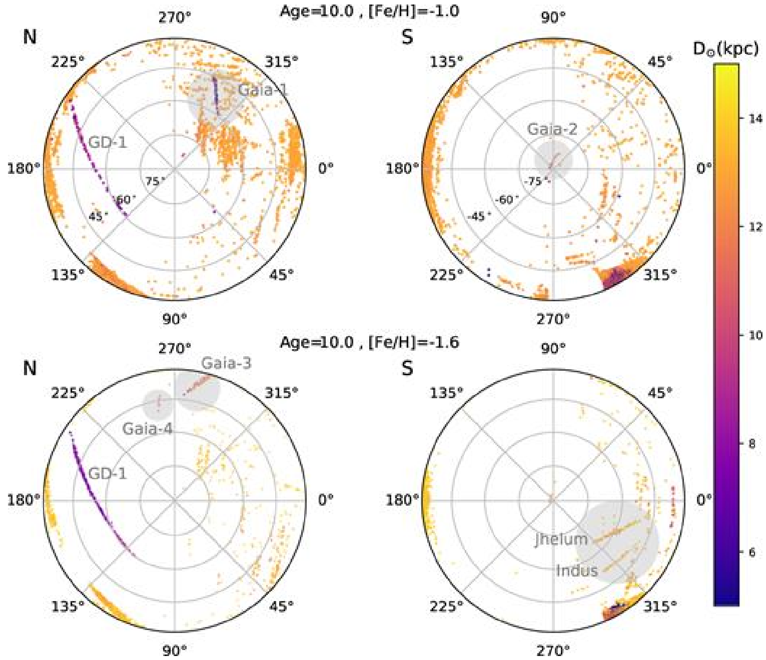

Figure 1. Chart demonstrating potential stream stars identified in (K. Malhan et al. 2018). This evidences the astounding capability we have to identify these objects, however this only accounts for a small portion of all stream stars.

3. METHODS

To achieve such goals many of the functions devised during classes and labs will be used. First the relevant snap shots from the simulation will be selected. In this case snap shots before and after each MW-M31 interaction will be the most useful, so around 3.8 Gyr ("M33_260.txt"), 5.9 Gyr ("M33_420") and beyond 6.5 Gyr ("M33_460"). Since stars are being addressed, only disk particles will be used. These points of interest can be clearly seen using the separation plot devised in Homework 6.

Now we have to find which particles are not bound to M33 at each of these moments. In order to do that we will be using the **Jacobi Radius**, which is defined as:

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

This equation takes in the mass of the satellite M33 (M_{sat}), the mass of the host MW+M31 (M_{host}) (only the mass sitting in between the center of mass and the satellite are accounted for at any moment) and r, which is the separation between these two.

Both masses can be easily obtained directly from the "GalaxyMass.py" function created in Homework 3. The separation, however, will require some extra steps. The base code will come from Homework 6, where we used the "CenterOfMass" class and created the "orbitCOM" function in order to plot the separation between each object in terms of time. For this project we will be using "orbitCOM" in order to obtain the separation for a given time and plugging that into the Jacobi Radius formula.

Then finally we will be able to use the code developed on Lab 7 to make plots for the velocity dispersion. The Jacobi radius will be used as a condition, so only particles beyond the Jacobi radius will be shown in the plots, allowing us to clearly see the characteristics and how they change from time to time during the merging event. See Figure 2 for reference. Furthermore I will also be plotting the velocity dispersion throughout time, and how the values change for it during the merger. Another plot that can be devised is one that looks at how the velocity dispersion changes for particles in terms of how far away they are from the M33 center of mass. These plots will all be deeply meaningful in understanding the dynamics in these streams and what observational data could expect from such events.

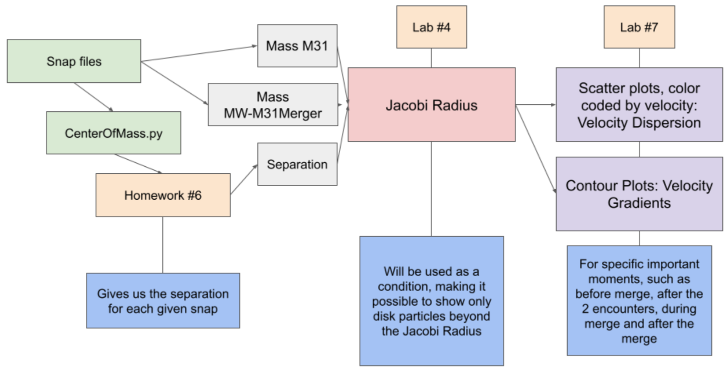

Figure 2. Diagram illustrating the steps that need to be taken in order to obtain velocity dispersion and gradient plots of particles located beyond the Jacobi radius (No longer bound by M33). In blue we can see more detailed explanations for how each function developed during an assignment will be used.

3.1. *Hypothesis*

I believe that, as the merging event advances, M33 will lose a large amount of the particles localized in its edges, most of it being during the major encounters of MW and M31, since its Jacobi radius will decrease since now both MW and M31 masses are exerting tidal forces. This will probably also mean we will see more extreme velocities beyond the Jacobi radius during those timeframes. Another prediction we can make is that as time passes these streams will slwoly be accreted by the now merged MW-M31 system, since this is what the ΛCDM model predicts.

4. RESULTS

The first figure created in this project (Figure 3) is a plot of Mean Velocity Dispersion vs. Time for particles beyond the Jacobi Radius of M33. This plot aims at demonstrating how the velocity dispersion for stream particles evolves throughout the merging event. The main takeaway from this plot is the fact that overall the velocity dispersion grows rapidly during the merging event, and at the rightmost part we can start to see some sort of stabilization in that dispersion. Another information that can be extracted from this plot are the peaks for this velocity dispersion, which could have some deeper meaning associated.

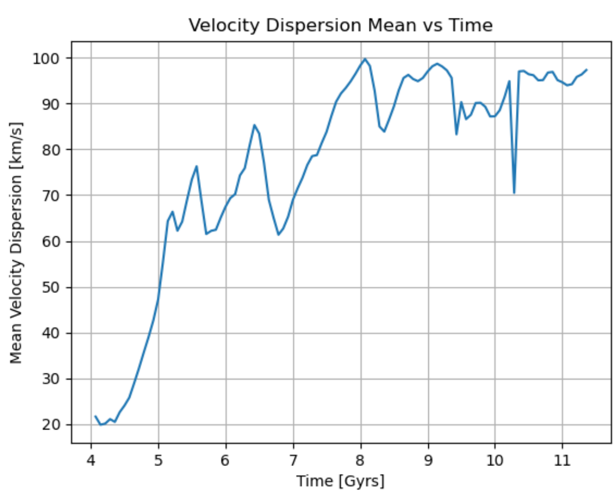

Figure 3. Plot demonstrating how the mean velocity dispersion of the stellar streams evolve throughout the collision of M31 and MW. With the mean velocity dispersion plotted on the y-axis and time on the x-axis. We can clearly see how the velocity dispersion for the stellar streams grows as the merger continues to happen.

The second figure generated for this project (Figure 4) is a series of Velocity Dispersion vs. Radial Distance plots, each for a given time during the merging event. The main objective of this plot is to portray the velocity dispersion profile of the stellar streams for some points in time during the merger. One of the takeaways of these plots is how the dispersion values grow with time, something we can also see in 3, but here we see that the dispersion also spreads in terms of position.

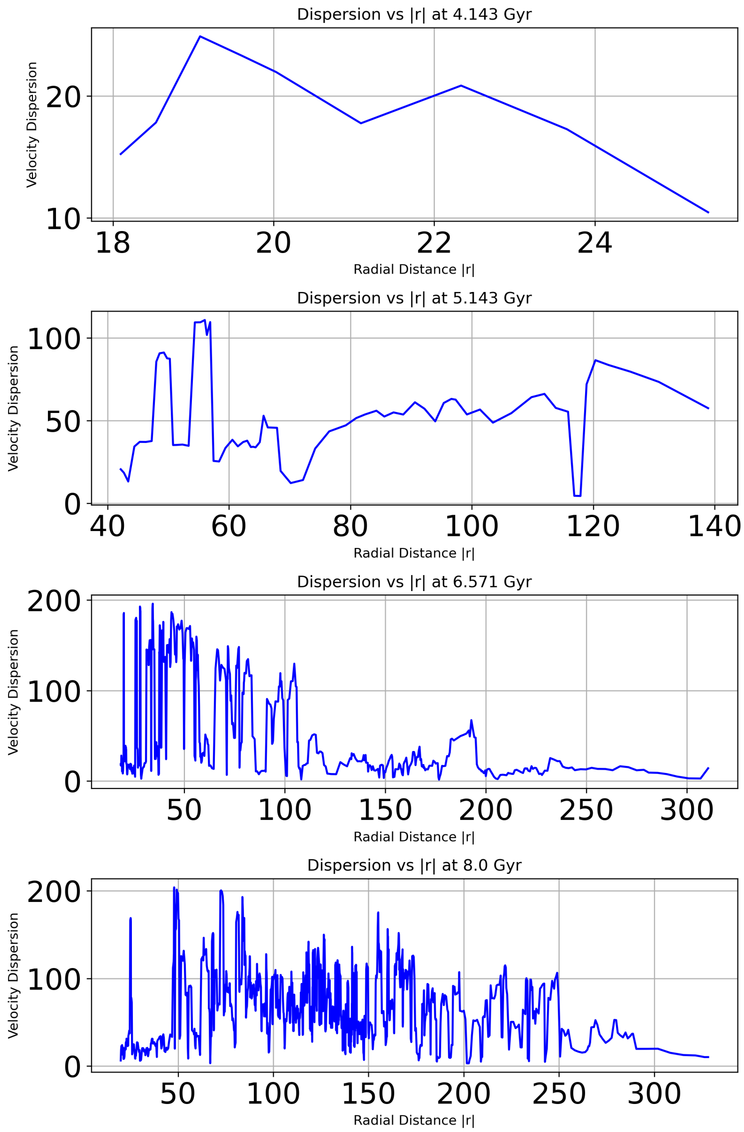

Figure 4. Plot demonstrating how the velocity dispersion looks like for different radii at key moments in time during the merger. Velocity dispersion is plotted in the y-axis and position (radius) in the x-axis. We can see some trends in the velocity dispersion profile, such as how the maximum values grow with time, and also where the regions with the most velocity dispersion are located at a given time

5. DISCUSSION

The first result that can be extracted from both Figure 3 and Figure 4 is that the velocity dispersion increases over time, as does the number of particles classified as stream particles. Both observations are consistent with my initial broad hypothesis. However, we now obtain even more detailed information, such as the dispersion profile, which allows for a deeper analysis of stellar streams.

The simulations conducted by J.-H. Choi et al. (2007) provide valuable insight into the structure of these streams under various scenarios. A key observation is that, over time, more particles leave the satellite and travel progressively farther from it—an effect that is also evident in my results. However, J.-H. Choi et al. (2007) focuses on the density and spatial distribution of the streams and does not examine their velocity dispersion. My results may therefore complement the simulation-based research on stellar streams by providing data on the velocities associated with this phenomenon and how they relate to the distance from the satellite.

A significant source of uncertainty—and indeed a limitation—in my analysis is the evolving mass profile of the MW–M31 system, which alters the Jacobi Radius of M33 in ways that my code does not currently account for. As a result, any conclusions drawn from the plots will inherently contain some degree of uncertainty in terms of the absolute Jacobi Radius at a given moment. This, in turn, affects the classification of particles as stellar stream members. However, this limitation does not affect the overall shape of the mean velocity dispersion curves shown in Figure 3 and Figure 4; any discrepancies could be addressed by applying a shift along the x-axis to adjust for the changing Jacobi Radius.

Another notable finding from my project is that, long after the onset of the merger, the velocity dispersion of stellar stream particles appears to stabilize at a significantly higher level than initially observed (Figure 3). This trend may reflect the process by which these particles become assimilated into the newly formed MW–M31 merged galaxy. Supporting this idea, Figure 4 shows that velocity dispersions at higher distances tend to increase as time passes, such that the farthest particles exhibit higher dispersions in the last snapshot used than seen previously. Additionally, the spatial extent of the stream increases over time, with its outer boundary expanding from 24 kpc at the beginning to 300 kpc in the final snapshot.

These findings are consistent with the ΛCDM model and predictions from J. Jensen et al. (2021), which suggest that stellar streams serve as a mechanism through which larger galaxies accrete material from smaller ones. Figures 3 and 4 offer valuable insight into the kinematic behavior of these particles after detachment from their original satellite, illustrating how their velocities evolve as they are stripped away. This information not only enhances our understanding of the final velocities of these particles as they approach the larger galaxy but also enables estimation of the relevant timescales for these events.

The uncertainties affecting this result are largely the same as those discussed earlier. While the overall profiles remain valid, a correction factor must be introduced to adjust the location of the Jacobi Radius in order to achieve the most accurate results.

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