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# Simulated Velocity Dispersion of Bar Stars in the Milky Way–M31 Merger

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## ABSTRACT

Bars are stellar structures in spiral galaxies whose torques drive angular momentum redistribution that propogate throughout their host galaxy. The destruction of a bar in a galaxy can signify the transformation of a spiral galaxy into an elliptical galaxy. To better understand gravitational interactions in the Local Group, van der Marel et al. (2012) produces an N-body simulation of the MW, M31, and M33 galaxies. I use this data to explore how the strength of the bar evolves, especially as it is impacted by the major galacic merger predicted by the simulation. I find a clear dimishing of the bar strength at the end of the simulation in M31 and MW. These findings demonstrate that merger-driven gravitational forces can eliminate bars in massive disks, thereby refining our picture of how interactions shape disk galaxy morphology.

## 1. INTRODUCTION

**Major mergers** in cosmology refer to the collision and subsequent consolidation of two spiral galaxies where the ratio of mass between the more massive galaxy and less massive galaxy does not exceed 4 (Wetzel et al. 2016). They represent one of the most dramatic processes that can alter the characteristics of a galaxy. The **dynamical friction** generated from individual gravitational force interactions between stars in each galaxy are great enough to destroy the elongated collection of stars near the center of each galaxy that fuels the galactic nucleus called the **stellar bar** (e.g., Knapen et al. 2002). Concurrently, major mergers destroy the dense spiral arms composed of young stars that define a **spiral galaxy** and convert it into an **elliptical galaxy**. which are identified by their ellipsoidal structure and older stellar population (Hubble 1936). Major mergers encapsulate a broader area of galactic structure and dynamics and by analyzing the evolution of stellar bars, we gain insight into the mechanisms that drive the overall transformation of galaxies (e.g., van der Marel 2001).

This topic is central to our understanding of the processes by which galaxies change over time, or **galactic evolution**. The disruption or alteration of the bar structure plays a critical role in the transformation of galactic geometry (Wu et al. 2018). After all, the definition of a galaxy as defined by Willman & Strader (2012) states "A galaxy is a **gravitationally bound** set of stars whose properties cannot be explained by a combination of baryons (gas, dust and stars) and Newton's laws of gravity", where "gravitationally bound" describes a system where the gravitational potential energy is stronger than the potential energy. Bar dynamics, while concerning a small fraction of the galactic population, exemplifies a region that demands scrutiny as the definition from Willman & Strader (2012) suggests. Furthermore, the presence and nature of bars significantly affects star formation and the secular evolution of galaxies (Schönrich & McMillan 2017). Understanding how mergers affect these structures helps elucidate the processes that cause barred spiral galaxies to transition into elliptical galaxies, ultimately shaping the observable characteristics of galaxies in the universe.

Current research indicates that major galactic mergers prompt significant changes in spiral galaxies, frequently leading to an evolution towards an elliptical shape (e.g., Mutch et al. 2011). Although simulations have successfully replicated some aspects of this transformation, the details of the intermediate stages remain poorly understood (Berentzen et al. 2003). The prevailing view is that the bar structure, characteristic of many spiral galaxies, is significantly disrupted during mergers (e.g., Mihos & Hernquist 1996; Mutch et al. 2011). The dynamics of stars within the bar are disturbed, leading to a chaotic dispersal throughout the merged galaxy, as shown in Fig. 1. Despite a qualitative understanding of the overall process, there exist gaps in our knowledge of the precise mechanisms at work.

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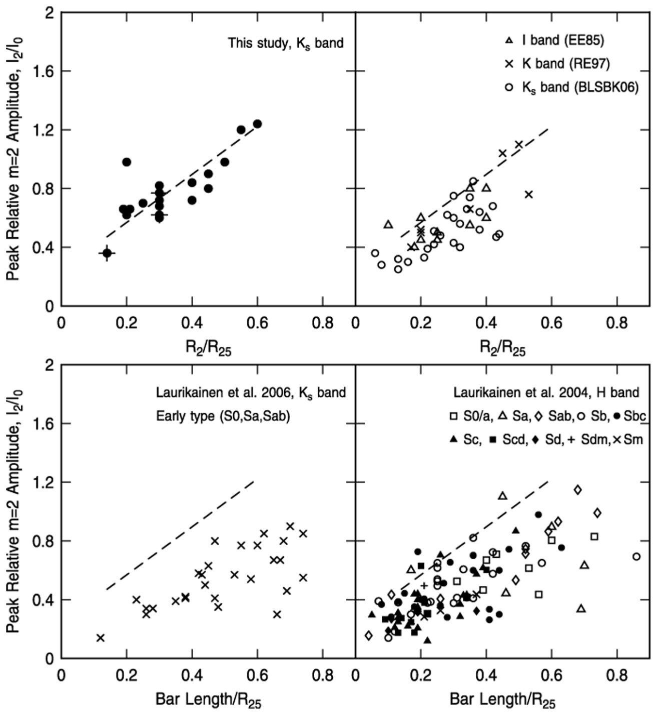


**Figure 1.** Figure 2 from Elmegreen et al. (2007). Peak relative amplitude of the Fourier component vs. the normalized radius at the peak. The different windows show galactic surveys delineated by emission detected (see Elmegreen et al. 2007). For all surveys, the bars that have higher peak relative amplitudes of the Fourier component are longer compared to their galaxy size.

Despite progress in simulating and observing galactic mergers, several open questions persist. The exact physical measurements and properties of bar structures in spiral galaxies are the subject of an ongoing debate, which greatly influences the evolution of galactic centers during a merger (Rathore et al. 2024). Furthermore, it is partially unclear how individual perturbations during a merger contribute to the overall disruption of the bar, and how we can predict the detailed dynamics of these events (Berentzen et al. 2003). Addressing these uncertainties is vital for developing a more comprehensive model of galaxy evolution post-merger, ultimately enhancing our understanding of the lifecycle of galaxies.

## 2. THIS PROJECT

Here, I study the influence the major merger predicted between the Milky Way and Andromeda (M31) galaxies

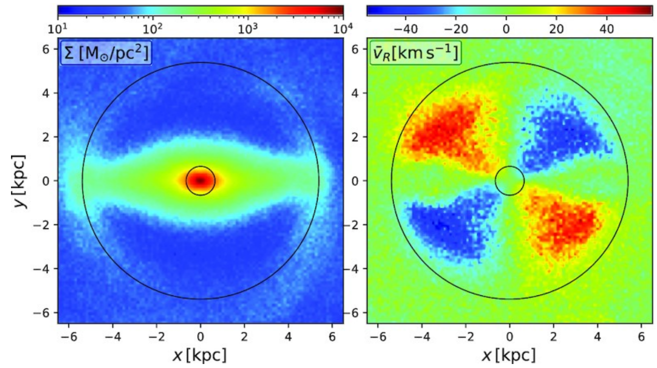


**Figure 2.** Figure 7 from Dehnen et al. (2023). The visual demonstrates one method used to determine the bar size and shape. This figure is generated from simulation snapshots, which mirrors the method I discuss later in the proposal.

as simulated in van der Marel et al. (2012) has on the strength of the peak of the Fourier amplitude in each constituent galaxy.

I use a modified classification for the stellar bar from Dehnen et al. (2023) to determine how force interactions between stars contribute to the overall disruption of the bar during a major merger.

The destruction of a bar indicates the evolution from a barred spiral galaxy to an elliptical galaxy. With respect to this, the overall structure of a galaxy dependent on the strength of a bar if present and understanding the evolution of the bar is tantamount to understanding galactic evolution in terms of galactic shape, star formation, and the ultimate fate of the Local Group.

## 3. METHODOLOGY

This manuscript uses data from van der Marel et al. (2012). This is an optimized N-body simulation containing stars in the disk and bulge of MW, M31, and M33. An N-body simulation is a simulation in which each timestep involves a gravitational force calculation between each particle and all other particles, finding the net acceleration and applying that to an orbit integration method. van der Marel et al. (2012) optimizes this method by grouping together weak force interactions that influence a particle in the same direction and neglecting very weak force interactions. This simulation models the dynamics of the Local Group as it experiences a major merger.

To perform any analysis on the barred region of a spiral galaxy, one must first define the bar. As previously discussed, this remains an active area of research (Berentzen et al. 2003). For this project, I employ the method depicted in Fig. 2 from Dehnen et al. (2023) due to our analogous methodologies. For this paper, I use the high-resolution positional disk and bulge star data from van der Marel et al. (2012) to employ the method from Dehnen et al. (2023). After identifying the stars located in their host galaxy's bar, I write a function that identifies close encounters between the Milky Way and M33 and generates a list of snapshots with an interval of 16 at "quiet" intervals, an interval of 1 surrounding close encounters and interval sizes of 2, 4, and 8 to provide smooth transitions. At each snapshot, I calculate the bar strength.

My code will follow a modified version of the calculations from Appendix B of Dehnen et al. (2023). This first involves separating the galaxy into major annuli with a population of stars between $N_{\min}$ and $N_{\max}$ such that the maximum and minimum radius of each annulus are related by the equation $R_{i,\max}/R_{i,\min} < 10^{\Delta}$. I then create overlapping annuli halfway between the $N$ major annuli to create $2N-1$ annuli in total. I then run a Fourier analysis of each annulus to find the bar strength $|c_n|$ where $c_n = Me^{-2i\theta}$. Finally, the code takes the mass-weighted average amplitude and uses this as the strength of the bar at each snapshot.

I will generate a plot showing the evolution of the bar strength in MW and M31 to argue that the strength of the bar is virtually extinguished as the result of the major merger. At special snapshots depicting the initial state, final state, and states halfway between close encounters, I generate a plot of the bar strength with respect to distance from the galactic nucleus, as well as density contour plots from a face-down and cylindrical perspective that portray the bar structure of the Milky Way and M31 as well as their merger product. These plots allow me to address my proposal.

I expect that stars initially located further from the galactic center will exhibit higher velocities after dispersion.

## 4. RESULTS

At $t = 0.0$ Gyr, the strongest annulus in MW is located 2 kpc away from the center of MW and M31 is located 4 kpc away from the center of M31 as shown in Fig. 3. This structure is expected, since the strength of a bar can be approximated by its radial size (Rathore et al. 2024). Following close encounters, the barred structures are largely displaced, including very irregular structures close to the merger of MW and M31. After the merger product of MW and M31 stabilize into an elliptical galaxy, at $t = 11.43$ Gyr, there are no prominent spikes in any of the annuli and the strength of the annuli gradually decrease as distance from the center increases.

Calculating the mass-weighted average of the annuli generates a total strength of the bar for each galaxy. The evolution of the galactic bar strength is shown in Fig. 4. The first snapshot of M31 at $t = 0.0$ Gyr records a bar strength of 0.22, which gradually decreases until the first close encounter at 3.93 Gyr. Each close encounter causes extreme fluctuations in the graph caused by the chaotic gravitational interactions present during the merger. For times $t \gtrsim 7.5$ Gyr, the bar strength of M31 hovers at 0.09, which is less than half its initial value. MW demonstrates the same effect to a lesser degree, since the initial bar strength is much lower. The bar strength of MW starts at 0.14 and ends at 0.07, as shown in the top left panel of Fig. 3 as well.

## 5. DISCUSSION

My analysis demonstrated the hypothesized result that for M31 and MW, the bar strength is weakened and the bar structure is destroyed. This result is less certain for MW, with a lower initial strength. The bar structure of both galaxies is shown to deteriorate with time, as the bottom panels lack the clear bump for stars at radii expected of bar stars, instead appearing uniform with a gradual decrease at higher radii.

These results corroborated the results from Elmegreen et al. (2007), whereby barred spiral galaxies frequently lose any barred structure following a major galactic merger. This structure indicated that the merger product is an elliptical galaxy as expected (e.g., Mutch et al. 2011). This simulation provides an explanation

The weakening of the bars reproduces the expected results seen in Elmegreen et al. (2007) that observed galaxies with recent major-merger signatures systematically lack strong bars. This result consequently demonstrates the capabilities of an N-body simulation as a tool to explain phenomena observed in distant galaxies and predict future cosmic events. This structure indicated that the merger product is an elliptical galaxy as expected (e.g., Mutch et al. 2011).

My analysis focuses the simulation from van der Marel et al. (2012), which does not include gas. Therefore, the effects of stellar formation propogated by the major galactic merger are not considered. In addition, this project only attempts to use radial distance from galactic center to define the bar, which is susceptible to chaotic orbits that arise in the immediate aftermath of close encounters. Also, random fluctuations in radial distance create noise in the bar value. This is a product of the fact that the bar is a structure defined by the geometric configuration of billions of stars, as opposed to any compact structure.

## 6. CONCLUSIONS

Bars are stellar structures in spiral galaxies whose torques drive angular momentum redistribution that

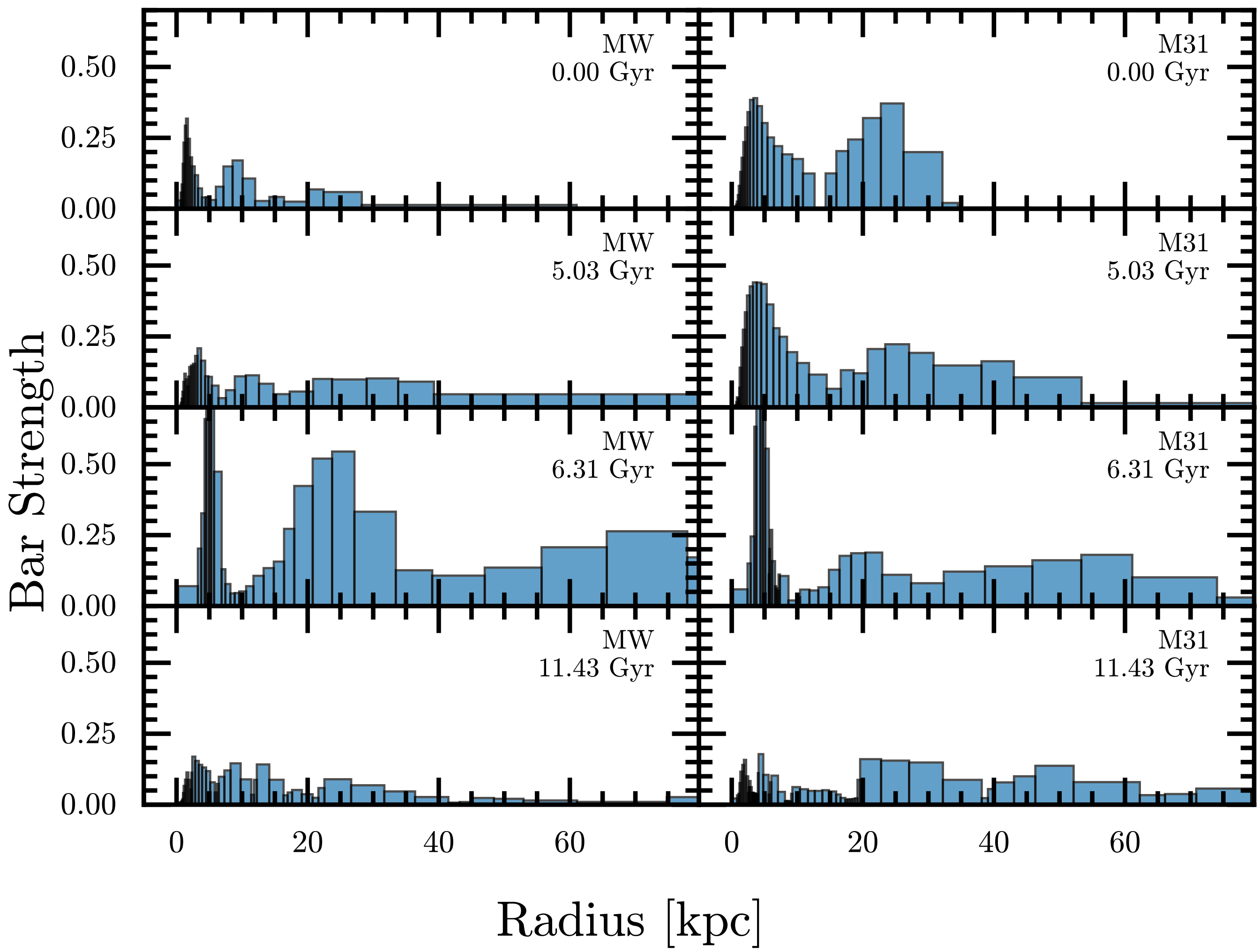


**Figure 3.** The bar strength of annuli in each galaxy generated as detailed in Sec. 3 at four select points between close encounters of MW and M31 bith respect to radial distance from the galactic center of mass of the host galaxy. The total galaxy strength is taken from the mass-weighted average strengths of the annuli. Annuli taken after the first close encounter lose the abundance of stars orbiting at $\sim 20\,\mathrm{kpc}$ away from the galactic center that characterize the bars of MW and M31

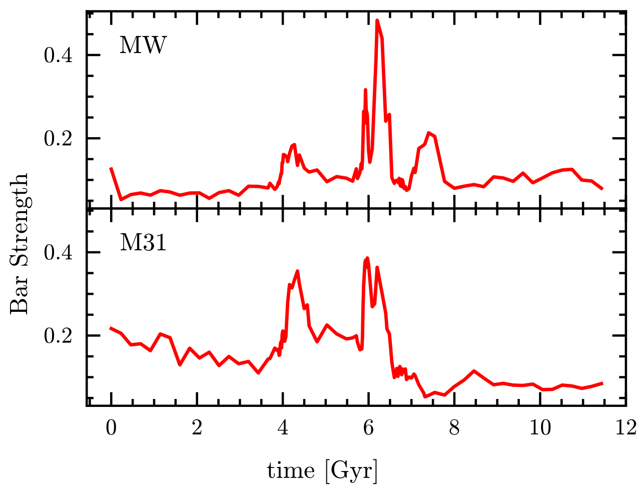


**Figure 4.** The measure of the mass-weighted average galaxy bar strength as detailed in Sec. 3 with respect to time elapsed from today $t = 0.0$. The close encounters between MW and M31 at 3.93 Gyr, 5.86 Gyr, and 6.71 Gyr (the last of which signifying the merger) are followed by large spikes in the bar strength lasting millions of years. For M31, we measure that the strength of the bar after the merger at the end of the simulation 11.4 Gyr is roughly 3 times weaker than today.

propogate throughout their host galaxy. The destruction of a bar in a galaxy can signify the transformation of a spiral galaxy into an elliptical galaxy. To better understand gravitational interactions in the Local Group, van der Marel et al. (2012) produces an N-body simulation of the MW, M31, and M33 galaxies. I use this data to explore how the strength of the bar evolves, especially as it is impacted by the major galacic merger predicted by the simulation.

The bars of both galaxies are diminished, with this effect most prominent in M31. Both the distribution of stellar annuli and bar strength of the entire galaxy evolve in patterns that can be explained through degradation of the barred galactic structure. These results indicate that stellar encounters during major mergers may destroy the bar structure and usher in the transfer from a spiral galaxy to an elliptical galaxy.

This project only considers the radius of stars with respect to the galactic center of mass. A comprehensive analysis of the 3D geometry of galaxies would abate the random noise that is otherwise unavoidable in 1D analysis. Better understanding of the geometry of bar configurations is needed to understand the precise mechanisms that take effect during major mergers. In addition, the simulation data from van der Marel et al. (2012), while robust, cannot capture the true complexity of the Local Group. Differences between results using the low- and high-resolution file can be extrapolated to suggest that increasing the resolution further may clarify results further in turn.

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*Software:* This work made use of the following software packages: `astropy` (Astropy Collaboration et al. 2013, 2018, 2022), `matplotlib` (Hunter 2007), `numpy` (Harris et al. 2020), `python` (Van Rossum & Drake 2009), and `scipy` (Virtanen et al. 2020; Gommers et al. 2025). Software citation information aggregated using `The Software Citation Station` (Wagg & Broekgaarden 2024; Wagg et al. 2024).

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