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

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1. INTRODUCTION

Major mergers in cosmology refer to the collision and subsequent consolidation of two spiral galaxies of similar size (e.g., Mutch et al. 2011). 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.

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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.

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, we study the influence the major merger predicted between the Milky Way and Andromeda (M31) galaxies as simulated in van der Marel et al. (2012) has on the strength of the peak of the Fourier amplitude in each constituent galaxy.

We use a modified classification for the stellar bar from Dehnen et al. (2023) to determine how force interactions

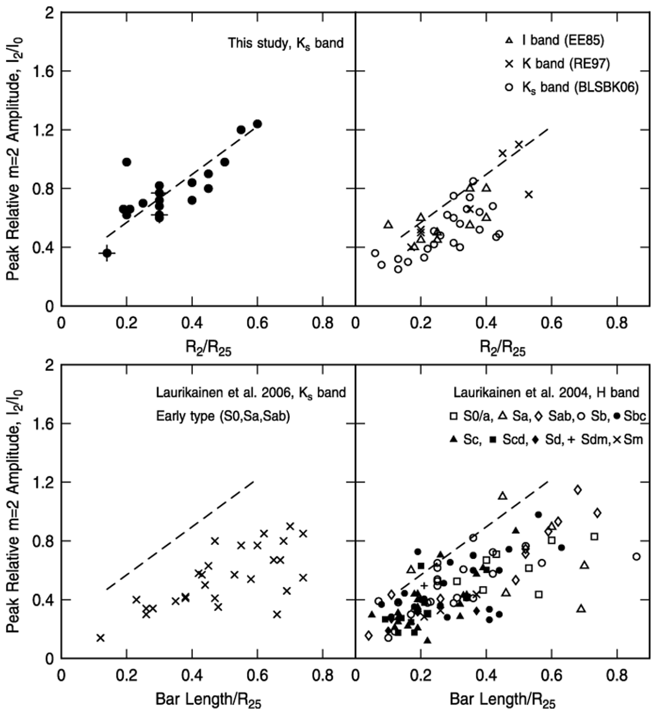

Figure 1. Figure 2 from Elmegreen et al. (2007). Peak relative amplitude of the Fourier component vs. the normalized radius at the peak. The different windows show galactic surveys delineated by emission detected (see Elmegreen et al. 2007). For all surveys, the bars that have higher peak relative amplitudes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

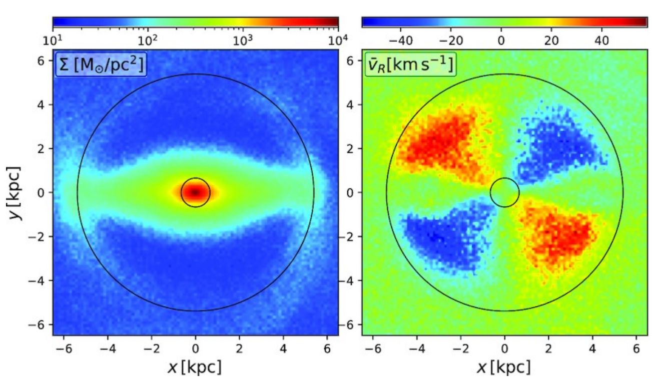

Figure 2. Figure 7 from Dehnen et al. (2023). The visual demonstrates one method used to determine the bar size and shape. This figure is generated from simulation snapshots, which mirrors the method I discuss later in the proposal.

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. This approach requires an input parameter θ that I obtain from the location of high-density regions in Fig. 3. 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 $c_n = \sum_m Me^{-im\theta}$. Finally, the code takes

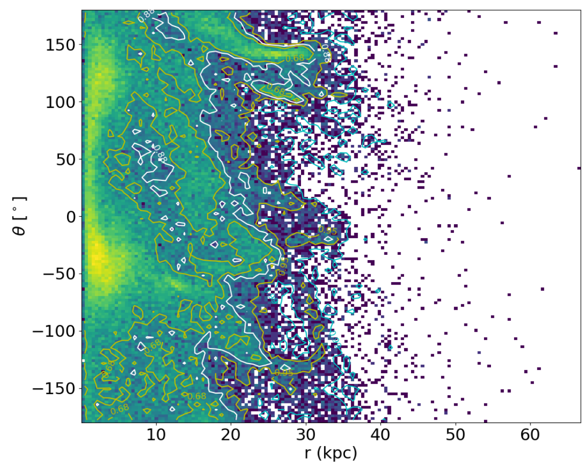

Figure 3. A histogram of M31 in polar coordinates (r, θ) onto $\mathbb{R}^2$ from Lab 7 from ASTR 400B Spring 2025 taught by Dr. G. Besla. This graph discretizes the stellar distribution, enabling us to identify the radius and principal angle of the bar. This analysis is used to determine the bar geometry for this project. By examining the density of the histogram, one can see that the bar appears most prominently at $\theta \approx -45^\circ$ and $\theta \approx 135^\circ$ Credit to G. Besla, R. Hoffman, R. Li, E. Patel, and myself for developing the code used to generate this figure.

the maximum 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.

Software: This work made use of the following software packages: `matplotlib` (Hunter 2007) and `python` (Van Rossum & Drake 2009). Software citation information aggregated using `The Software Citation Station` (Wagg & Broekgaarden 2024; Wagg et al. 2024).

REFERENCES

Berentzen, I., Athanassoula, E., Heller, C. H., & Fricke, K. J. 2003, MNRAS, 341, 343, doi: 10.1046/j.1365-8711.2003.06417.x

Dehnen, W., Semczuk, M., & Schönrich, R. 2023, MNRAS, 518, 2712, doi: 10/.1093/mnras/stac3184

Elmegreen, B. G., Elmegreen, D. M., Knapen, J. H., et al. 2007, ApJL, 670, L97, doi: 10.1086/524359

Hubble, E. P. 1936, Realm of the Nebulae

Hunter, J. D. 2007, Computing in Science & Engineering, 9, 90, doi: 10.1109/MCSE.2007.55

Knapen, J. H., Pérez-Ramírez, D., & Laine, S. 2002, Monthly Notices of the Royal Astronomical Society, 337, 808. https://api.semanticscholar.org/CorpusID:10845683

Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641, doi: 10.1086/177353

Mutch, S. J., Croton, D. J., & Poole, G. B. 2011, The Astrophysical Journal, 736, 84, doi: 10.1088/0004-637x/736/2/84

Rathore, H., Choi, Y., Olsen, K. A. G., & Besla, G. 2024, The Astrophysical Journal, 978, 55, doi: 10.3847/1538-4357/ad93ae

Schönrich, R., & McMillan, P. J. 2017, MNRAS, 467, 1154, doi: 10.1093/mnras/stx093

van der Marel, R. P. 2001, AJ, 122, 1827, doi: 10.1086/323100

van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012, The Astrophysical Journal, 753, 9, doi: 10.1088/0004-637X/753/1/9

Van Rossum, G., & Drake, F. L. 2009, Python 3 Reference Manual (Scotts Valley, CA: CreateSpace)

Wagg, T., & Broekgaarden, F. S. 2024, arXiv e-prints, arXiv:2406.04405. https://arxiv.org/abs/2406.04405

Wagg, T., et al. 2024, TomWagg/software-citation-station: v1.2, v1.2, Zenodo, doi: https://doi.org/10.5281/zenodo.13225824

Willman, B., & Strader, J. 2012, AJ, 144, 76, doi: 10.1088/0004-6256/144/3/76

Wu, Y.-T., Pfenniger, D., & Taam, R. E. 2018, ApJ, 860, 152, doi: 10.3847/1538-4357/aac5e8