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Galaxy Evolution Through Tidal Interactions: Evolution of the Observed and Mass Derived Rotation Curves of M31 and the Milky Way

Colton Quirk[1]

[1] *University of Arizona*

ABSTRACT

This project analyzes the impact of tidal interactions on rotation curves of galaxies. This aids in our understanding of galaxy evolution as it elucidates the impact of tidal interactions on the kinematics of the galaxy. This work utilized data from an N-body simulation of the Milky Way and Andromeda galaxies. This work seeks to explore the relationship between the distance between the Milky Way and Andromeda and the change in the rotation curves. We found that there is a negative correlation between the separation and the deviation of the rotation curves. Additionally, it was found that there is a separation at which there is a maximum deviation; this separation is $123kpc$ for Andromeda but $173kpc$ for the Milky Way. These distances are not the minimum distance between M31 and the MW in the simulation. This suggests that there is a separation at which tidal forces have the strongest impact on galaxy kinematics, which is not during the merger.

Keywords: Galaxies (573) — Rotation Curve (619)—Stellar Disk (1594) —Major Merger (-)–Hernquist Profile (-)–

1. INTRODUCTION

The study of galaxy evolution is crucial to understanding the large-scale structure of the universe and the mechanisms that drive changes in galactic morphology and kinematics. One key aspect of galaxy evolution is the role of tidal interactions in shaping the observed and mass-derived **rotation curves** of **galaxies**. Galaxies are gravitationally bound systems of stars, gas, dust, and dark matter. Rotation curves are plots of orbital velocity versus distance from the galaxy center, typically they are analyzed using the **Stellar Disk** component of the galaxy. The stellar disk is the flattened, rotating component of a galaxy where most of its stars and gas reside, typically exhibiting spiral structure in disk galaxies. This project focuses on the evolution of the rotation curves of the Milky Way and M31 (the Andromeda Galaxy), particularly how their disk and bulge components respond to gravitational interactions over time. Tidal interactions are the gravitational forces that arise from interactions between spatially extended objects, not point-sources (E. R. Dimitri Gadotti 2016). As the two galaxies move towards each other, the parts of the galaxy closest to each other will feel a different amount of gravitational force than the parts of the galaxy farther from each other. This will cause the structure of the galaxies to change. This process of a galactic collision between two galaxies of comparable mass, significantly altering their structure and triggering dynamical transformations, is referred to as a **Major Merger**. This project will study how the galaxies change by analyzing the rotation curves of each galaxy, for both the disk stars and the bulge stars. Rotation curves provide insight into the mass distribution of galaxies, distinguishing between visible and dark matter contributions. By examining how these curves evolve through tidal interactions, we can gain a clearer picture of the dynamical history of these galaxies and their future trajectories.

Understanding the evolution of rotation curves is fundamental to deciphering how galaxies grow, interact, and redistribute their mass. The discrepancy between observed and mass-derived rotation curves has been a longstanding issue in astrophysics, offering evidence for dark matter or alternative gravitational theories. Studying these curves in the Milky Way and M31 allows us to explore how tidal interactions, such as satellite mergers, close encounters, and long-range gravitational influences, reshape the internal dynamics of galaxies (P. L. T. Dusan Keres 2007). Since both the Milky Way and M31 are on a collision course, analyzing their past and present rotation curves provides a valuable window into how interactions impact galactic structure, angular momentum distribution, and the overall dark matter profile.

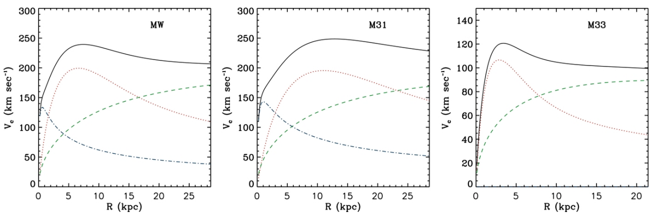

Figure 1. Model rotation curves showing the contributions of the various parts of the galaxies to the rotation curve. This work seeks to demonstrate the evolution of the rotation curves throughout the first close encounter of M31 and the MW.

Our current understanding of galactic rotation curves stems from both observational and theoretical studies. Observations of spiral galaxies indicate that their rotation curves remain nearly flat at large radii, implying the presence of extended dark matter halos (E. R. Dimitri Gadotti 2016). Theoretical models and N-body simulations suggest that tidal interactions can redistribute mass within a galaxy, potentially altering both the baryonic and dark matter components (R. G. T. S. Jay Anderson 2012). In particular, major interactions, such as mergers or flybys, can lead to angular momentum transfer, bulge growth, and changes in the mass-to-light ratio, all of which impact the rotation curve.

Despite significant progress, many open questions remain regarding the evolution of rotation curves under tidal influences. How exactly do tidal interactions reshape the mass distribution of the disk and bulge over different timescales (R. A. F. B. W. Rachel S. Somerville 2015)? Do observed changes in rotation curves primarily reflect baryonic redistribution, or do they hint at modifications in the dark matter halo? Additionally, while we can model individual interactions, predicting long-term evolutionary trends remains challenging due to the complex interplay between baryons, dark matter, and external forces. Finally, as the Milky Way and M31 move toward their eventual merger, how will their respective rotation curves evolve, and what can this tell us about the fate of similar galactic interactions throughout cosmic history? Addressing these questions will enhance our understanding of galaxy evolution and the nature of dark matter.

2. THIS PROJECT

This project investigates how the rotation curves of the Milky Way and Andromeda (M31) galaxies are influenced by tidal interactions as they approach their first close encounter in a future galactic collision. Specifically, we analyze the changes in rotation velocity profiles as a function of radius during the different stages of their interaction. Using an N-body simulation of the Milky Way–M31 system, we extract rotation curves at multiple time snapshots and quantify how the gravitational pull of the approaching galaxy perturbs the internal dynamics and mass distribution of the other. The central goal is to identify the degree, timing, and nature of deviations in rotation curves that result from mutual tidal forces, especially during close passages.

This work addresses the open question posed in the introduction: "How will the rotation curves of the Milky Way and Andromeda evolve as they move closer together?" This question is part of a broader effort to understand how gravitational interactions between galaxies shape their internal dynamics before a merger. While the long-term merger remnant structure has been studied extensively, less is known about the short-term kinematic signatures, such as changes in rotation curves, that precede coalescence. This project provides a focused analysis on this phase, helping to fill a gap in our understanding.

Understanding how tidal forces affect the rotation curves of galaxies during an interaction is critical for interpreting observations of galaxies in the early stages of mergers. Since rotation curves are often used to infer mass distributions and the presence of dark matter, failing to account for the effects of nearby companions could lead to misinterpretations. By providing a detailed, simulation-based study of how the Milky Way and Andromeda affect one another before merging, this project contributes to a clearer picture of galaxy evolution in interacting systems. The findings will help clarify which kinematic features are transient and which reflect underlying mass distributions, refining our models of galactic structure and dynamics.

3. METHODOLOGY

The data utilized in this project is an N-body simulation of the evolution of the Milky Way and M31R. G. T. S. Jay Anderson (2012). An N-Body simulation is a numerical simulation that takes the locations and velocities of N objects/"bodies" and evolves their positions and velocities over time. For each timestep, the forces of each body are calculated by summing the forces due to all other bodies in the simulation to determine the acceleration of the body for that time step. This is done for all objects, and then the positions and velocities are evolved in the next timestep. In this simulation, the Milky Way and M31 are modeled using three classes of "particles." These particle types are 1. Dark Matter Halo particles, 2. Stellar Disk Particles, and 3. Galaxy Bulge Particles. The Dark Matter Halo particles are modeled using a Hernquist Profile. The Hernquist Profile is a spherically symmetric model used to describe the density distribution of a galaxy's stellar bulge or dark matter halo, given by $\rho(r) = \frac{M}{2\pi} \cdot \frac{a}{r(r+a)^3}$. It features a central cusp and finite total mass, and provides analytic expressions for both the gravitational potential and enclosed mass. The profile is widely used in simulations because it closely mimics the observed light profiles of elliptical galaxies while remaining computationally efficient.

For this project, I will be modeling the rotation curves of the Stellar Disk Particles, particle type 2. These are chosen as they represent the stellar matter within the galaxy. As well, we will use the LowRes data, which incorporates approximately half of the total particles in the HighRes data. This data was chosen for a mix of detail within the simulation, as well as speed in calculating the rotation curves and various features. For this project, we chose to use the snapshots between snap number 0 and snap number 350, taking every 10th snapshot. These snapshots were chosen as they cover the first major interaction between M31 and the Milky Way. For each snapshot, rotation curves will be calculated using the "observed" rotation curve and mass-derived rotation curves. Then the deviation of the rotation curves from the initial snapshot, snap number 0, will be calculated. Additionally, we will measure the deviation between the observed rotation curves and the mass-derived rotation curves. The separations between the Milky Way and Andromeda will be calculated for each snapshot so we can plot the deviation of the rotation curves versus the separation between the Milky Way and Andromeda.

The mass-derived rotation curves are calculated by taking radial slices of the galaxy and measuring the mass within each slice. Then, we can calculate the velocity needed for a particle to have a circular orbit around that mass at that radial slice.

$$F = m\overrightarrow{a} = m\frac{v^2}{r} = \frac{GMm}{r^2} \tag{1}$$

We can solve this equation for the velocity of a circular orbit.

$$v_{\mathrm{circ}} = \sqrt{\frac{GM}{r}} \tag{2}$$

This circular velocity would be calculated for each radial slice by measuring the amount of mass within that radial distance. See Figure 2 for an example of a mass-derived rotation curve of M31.

The "observed" rotation curve is the line-of-sight velocity field when viewed edge-on. This will be constructed for each snapshot for each galaxy and particle type. This will be made using the same technique as used in Lab 7 of this course. That is, we will take the

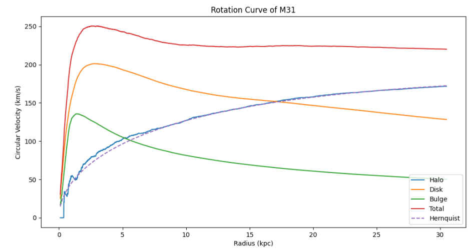

Figure 2. Mass-derived rotation curve for M31 at snap number 0. This was made for Homework 5.

galaxy and rotate it so that its angular momentum is aligned with the z-axis. Then, we will plot the particles' velocities versus their x-coordinate (relative to the center of mass of the galaxy) as a 2D histogram. This will construct a rotation curve of the galaxy for a particular snapshot. See Figure 3 for an example of an "observed" rotation curve.

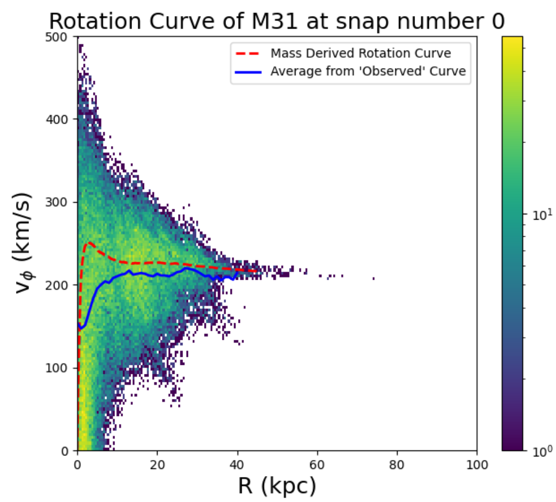

Figure 3. Initial rotation curve.

Thus, the overall process for finding how the rotation curves change over time is shown below. This process will be completed for both galaxies.

1. Load the data for a particular snapshot
2. Create a MassProfile object
3. For each MassProfile object, create a mass-derived rotation curve using equation 2
4. For each MassProfile, rotate the frame of the galaxy such that the angular momentum aligns with the z-axis
5. Then plot the x-coordinate versus the velocity of the particles as a 2D histogram

6. Save both of these profiles and continue to the next snapshot

These rotation curves will then be overplotted to show how the "observed" and mass-derived rotation curves align. Additionally we will compute the mean squared deviation from the initial rotation curve, and the deviation between the mass-derived and average observed rotation curves. This will be done for each of the selected snapshots. The separation between the Milky Way and Andromeda will also be calculated for each time step. This will enable us to create two plots, for each galaxy, of the deviation from initial rotation curve, and deviation from mass-derived rotation curve when compared to the separation between the two galaxies. This allows us to identify if the tidal interactions between M31 and the Milky Way impact the rotation curve.

We hypothesize that as the separation between M31 and MW decreases, the deviation from the initial curve will increase. As well, the deviation from the mass-derived rotation curve will increase. That is, there is a negative correlation between the deviation from the initial rotation curve, or deviation from the mass-derived rotation curve, and the separation of MW and M31. The maximum deviation is expected to occur at the minimum separation between MW and M31.

4. RESULTS

Figure 4 shows the rotation curves over time for M31, as well as their deviations from the initial rotation curve. The top graph shows just the observed rotation curves for each chosen snapshot. The bottom graph shows the difference between the initial rotation curve, the rotation curve at snap number 0, and the various rotation curves. Rotation curves seem to be getting slower over time, that is, the maximum velocity of the rotation curve decreases.

Figure **??** shows the root mean squared error of the deviations versus the separation between the galaxies. The graph shows a general trend where the deviations increase with distance. Additionally, there is a clear region where the deviations from the initial curve increase drastically. For the Andromeda Galaxy, the maximum deviation occurs at $123kpc$. This indicates that there is a region for which the tidal interactions impact the kinematics of the galaxy the most, which is not the minimum distance between the galaxies.

5. DISCUSSION

The deviations increase with a decrease in separation. This does agree with the hypothesis that the rotation curves do not fit as well with the circular rotation curves as the separation decreases. However, it does not di-

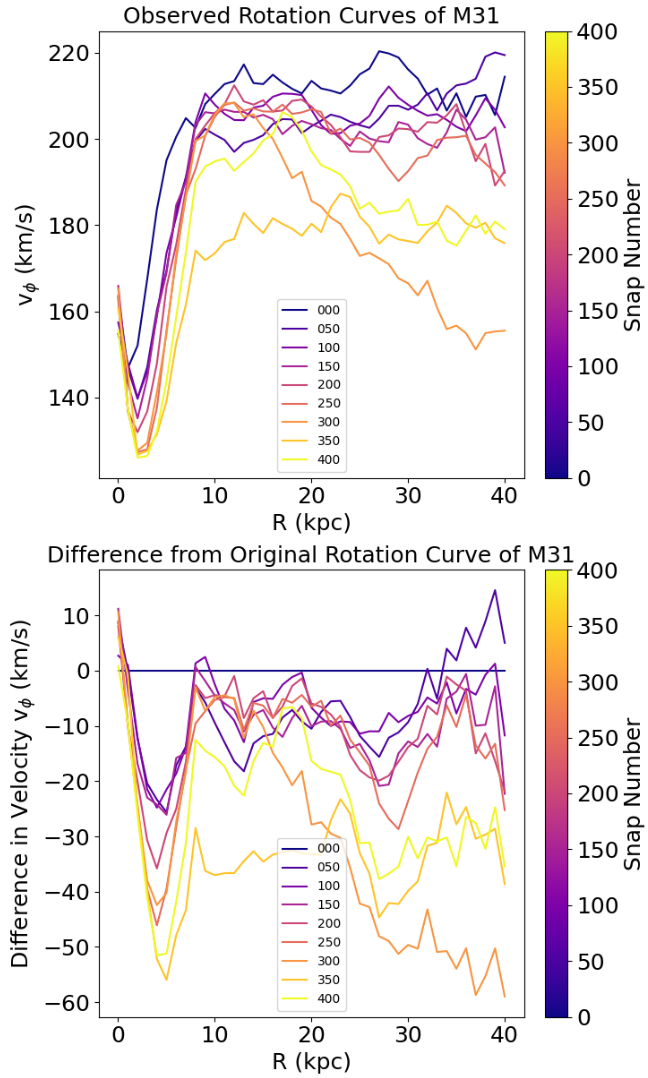

Figure 4. Rotation Curves of M31 during various snapshots. The difference between the rotation curves at various snapshots and the initial rotation curve at Snap number 0.

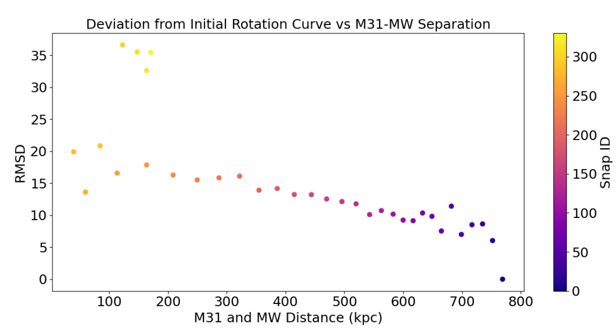

Figure 5. Root Mean Square Error Deviation from the initial rotation curve versus the separation between M31 and the Milky Way. As the Milky Way and M31 approach each other, the distance decreases, and the rotation curves deviate more, that is, they have a higher RMSD value from the initial rotation curve.

rectly relate to the distance. There is a specific separation at which the deviations are maximum, below which the deviations follow a similar trend to further separations. This suggests that there is a separation at which the tidal interactions are maximum, but within that separation, M31 and MW may act as a single galaxy, and the deviations are not as extreme. This disagrees with the hypothesis that the maximum deviations would occur when the galaxies are at the minimum separation.

These results support and refine prior findings in the literature regarding the impact of tidal interactions on galactic kinematics. Previous studies have shown that interactions between galaxies can lead to significant distortions in rotation curves, particularly during the early stages of an encounterS. E. E. E. Katrick Sheth (2016). Our finding that the deviations peak at an intermediate separation rather than at the point of closest approach suggests a more nuanced view: the strongest tidal effects on kinematics may not coincide with minimum distance, but rather occur when the galaxies are close enough to interact strongly while still maintaining distinct mass distributions. This adds complexity to current models of galaxy evolution, emphasizing that tidal effects are not simply a function of proximity but are modulated by structural dynamics and mutual gravitational influence. Such insights are crucial for interpreting the kinematic signatures of galaxy pairs and for constraining the timeline and physical mechanisms driving their coalescence. There are several sources of uncertainty in my analysis. First, the choice of radial bin size directly affects the smoothness and resolution of the rotation curves—larger bins may obscure localized features, while smaller bins introduce more noise due to fewer particles per bin. Additionally, aligning and comparing snapshots between galaxies with evolving centers and orientations adds further uncertainty to the determination of true separation and relative kinematics. Lastly, the root-mean-squared-deviation analysis is potentially largely impacted by the extreme deviations, and another measurement of deviations could be utilized in future analysis.

6. CONCLUSION

This project analyzes the impact of tidal interactions on rotation curves of galaxies. This aids in our understanding of galaxy evolution as it elucidates the impact of tidal interactions on the kinematics of the galaxy. This work utilized data from an N-body simulation of the Milky Way and Andromeda galaxies. This work seeks to explore the relationship between the distance between the Milky Way and Andromeda and the change in the rotation curves.

One interesting aspect of the analysis was that the tidal interactions had the strongest impact on the rotation curves of the galaxies before the minimum separation between the galaxies. The largest deviation was found to be at 123 Mpc for Andromeda and 171 Mpc for the Milky Way. This potentially indicates that tidal interactions affect the galaxies before a collision. This disagreed with our hypothesis that the maximum deviation would occur when the separation between the galaxies was smallest.

One thing that would be interesting to add to this analysis is a spatial map of the deviations from the mass-derived rotation curves over time. This would allow us to see if the side of the MW or M31 that is closer to the other galaxy experiences greater deviations. This would show more clearly how the tidal interactions between MW and M31 impact the rotation curves. As well, this may lead to an understanding of why there is a radius at which the deviations are maximum, and below which the deviations shrink. A more detailed analysis of the actual force experienced by the stars within the galaxies would also lead to a greater understanding of the tidal interactions.

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1. Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/15383881/aabc4f)
2. matplotlib Hunter (2007), DOI: 10.1109/MCSE.2007.55
3. numpy van der Walt et al. (2011), DOI: 10.1109/MCSE.2011.37
4. scipy Jones et al. (2001–), Open source scientific tools for Python. http://www.scipy.org/
5. ipython Perez & Granger (2007), DOI: 10.1109/MCSE.2007.53

REFERENCES

Dimitri Gadotti, E. R. 2016, Galactic Bulges (Springer)

Dusan Keres, P. L. T. 2007, The Astrophysical Journal

Jay Anderson, R. G. T. S. 2012, The Astrophysical Journal

Katrick Sheth, S. E. E. E. 2016, The Astrophysical Journal

Rachel S. Somerville, R. A. F. B. W. 2015, Monthly Notices of the Royal Astronomical Society