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

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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. 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 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.

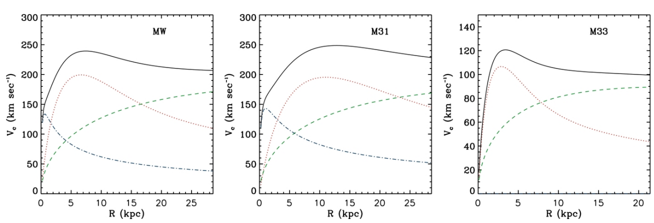

Figure 1. Model rotation curves showing the contributions of the various parts of the galaxies to the rotation curve. This work seeks to demonstrate the evolution of the rotation curves throughout the first close encounter of M31 and the MW.

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 seeks to answer how the rotation curves of the Milky Way and the Andromeda galaxy change over time. For example, do the rotation curves maintain a flat profile throughout the merger? If they do not maintain a flat profile, when and why does it deviate? As well, this project will analyze how the disk and bulge particles within the galaxies are affected by the merger process. By answering these questions, we can gain significant insights into how mergers affect galaxy evolution.

3. METHODOLOGY

This project will analyze the rotation curves of the Milky Way and the Andromeda Galaxy throughout their merger. We will use all 802 snapshots for both galaxies using the VLowRes data. For each snapshot, we will construct four rotation curves. We will create rotation curves for both the disk-type and bulge-type particles, particle types 2.0 and 3.0, respectively. We will also construct two rotation curves, the mass-derived rotation curve and the "observed" rotation curve, for each particle type.

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.

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

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 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.

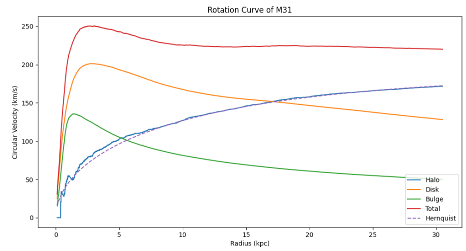

Figure 2. Mass-derived rotation curve for M31 at snap number 0. This was made for Homework 5.

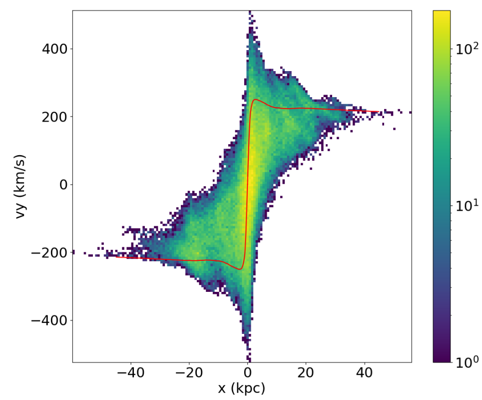

Figure 3. "Observed" rotation curve for M31 at snap number 0. This was made for Lab 7.

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. The rotation curves will then be added to an animation to show the evolution over time for both galaxies and particle types.

We hypothesize that the rotation curves will not maintain a flat profile throughout the merger. As the tidal forces disrupt the rotation of the galaxies, the rotation curves will be impacted. As discussed in R. A. F. B. W. Rachel S. Somerville (2015), there is a transfer of particles between the disc and the bulge of galaxies during mergers. This will affect the distribution of the galaxies' angular momentum during the merger, leading to variances in the rotation curves of the disc and bulge particles.

4. RESULTS

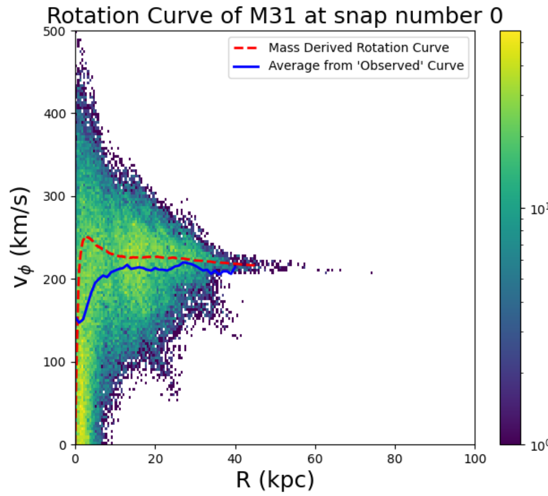

Figure 4. Initial rotation curve.

5. DISCUSSION

REFERENCES

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

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

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

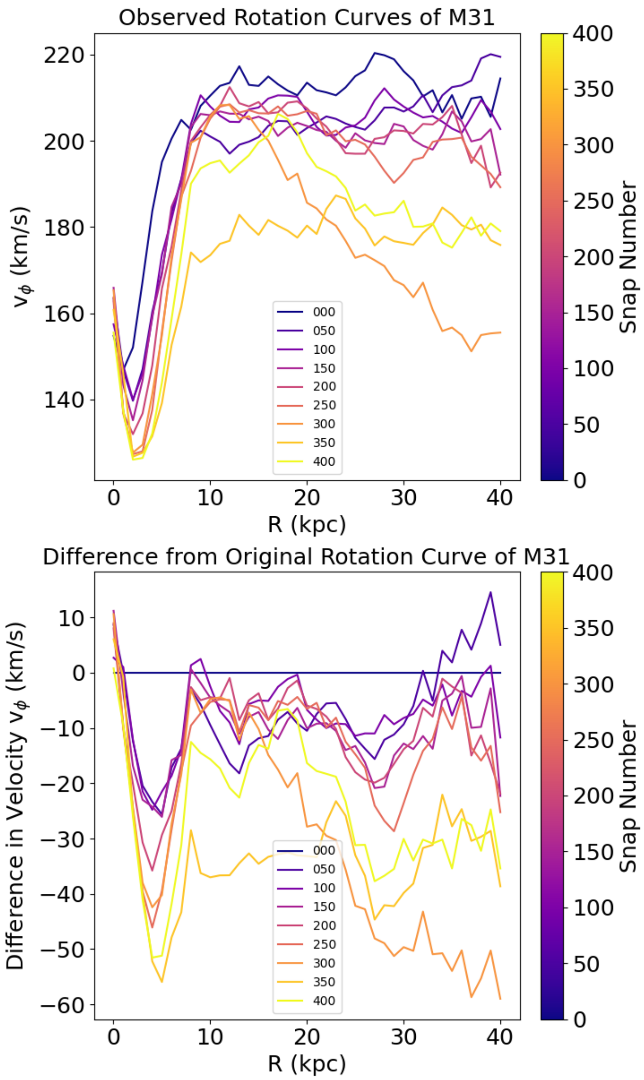

Figure 5. Rotation Curves of M31 during various snapshots. The difference between the rotation curves at various snapshots and the initial rotation curve at Snap number 0.

Appendix

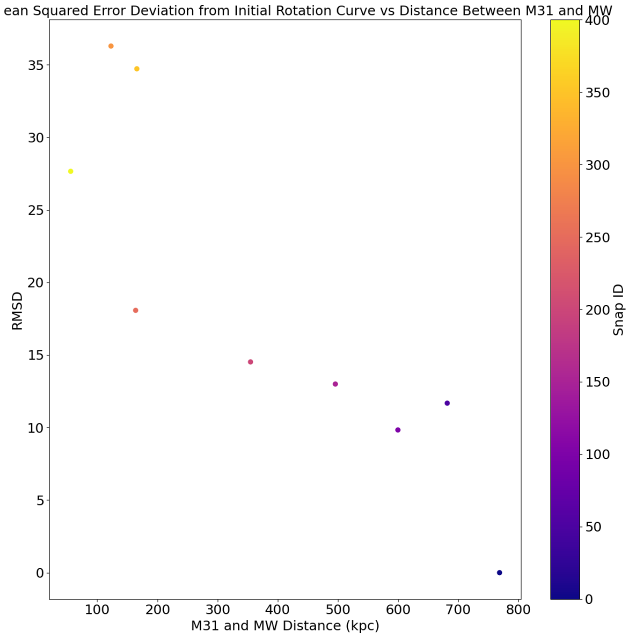

Figure 6. Root Mean Square Error Deviation from the initial rotation curve versus the separation between M31 and the Milky Way. As the Milky Way and M31 approach each other, the distance decreases, the rotation curves deviate more, that is, they have a higher RMSD value from the initial rotation curve.

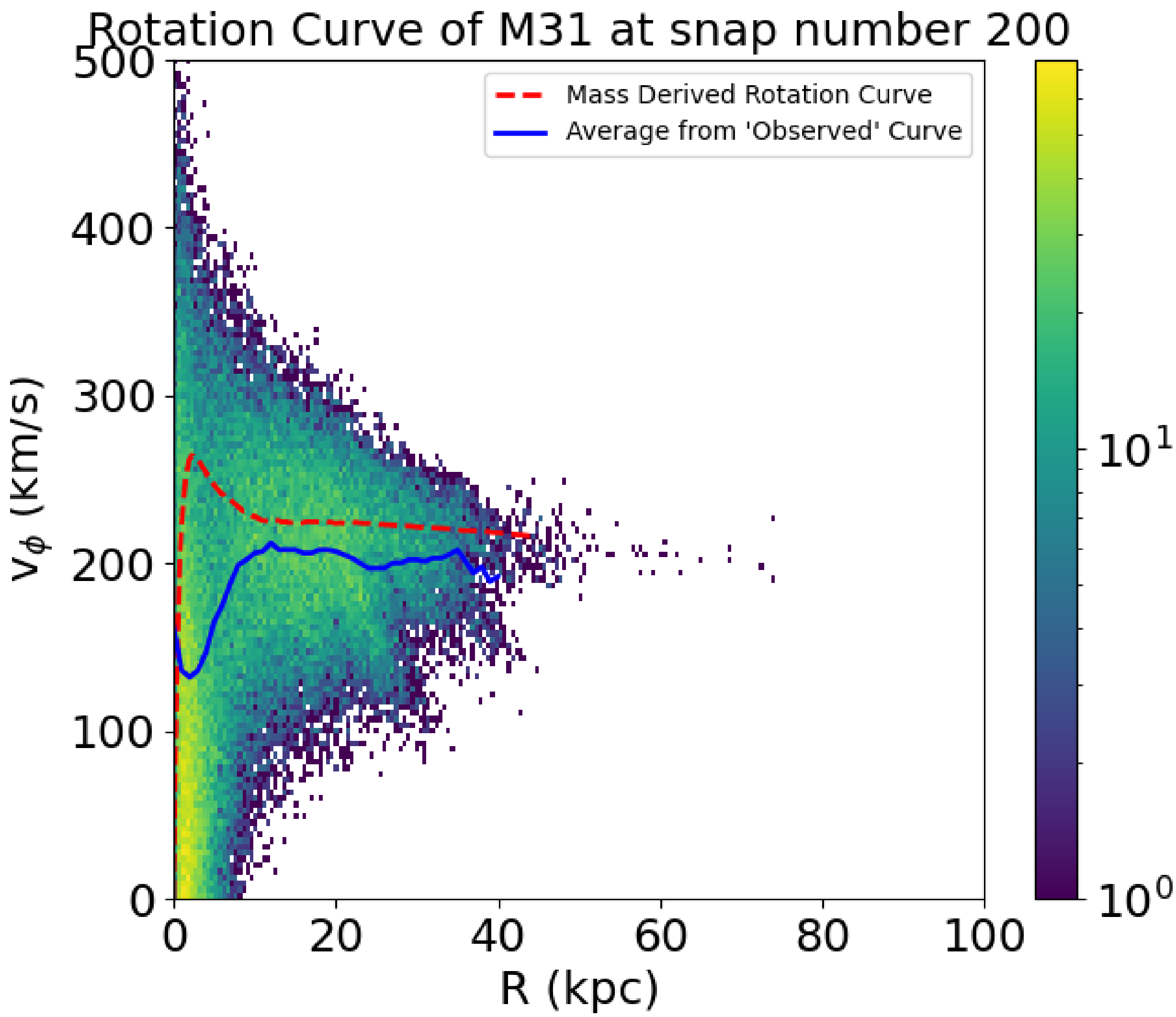

Figure 7. Rotation curve before close encounter.

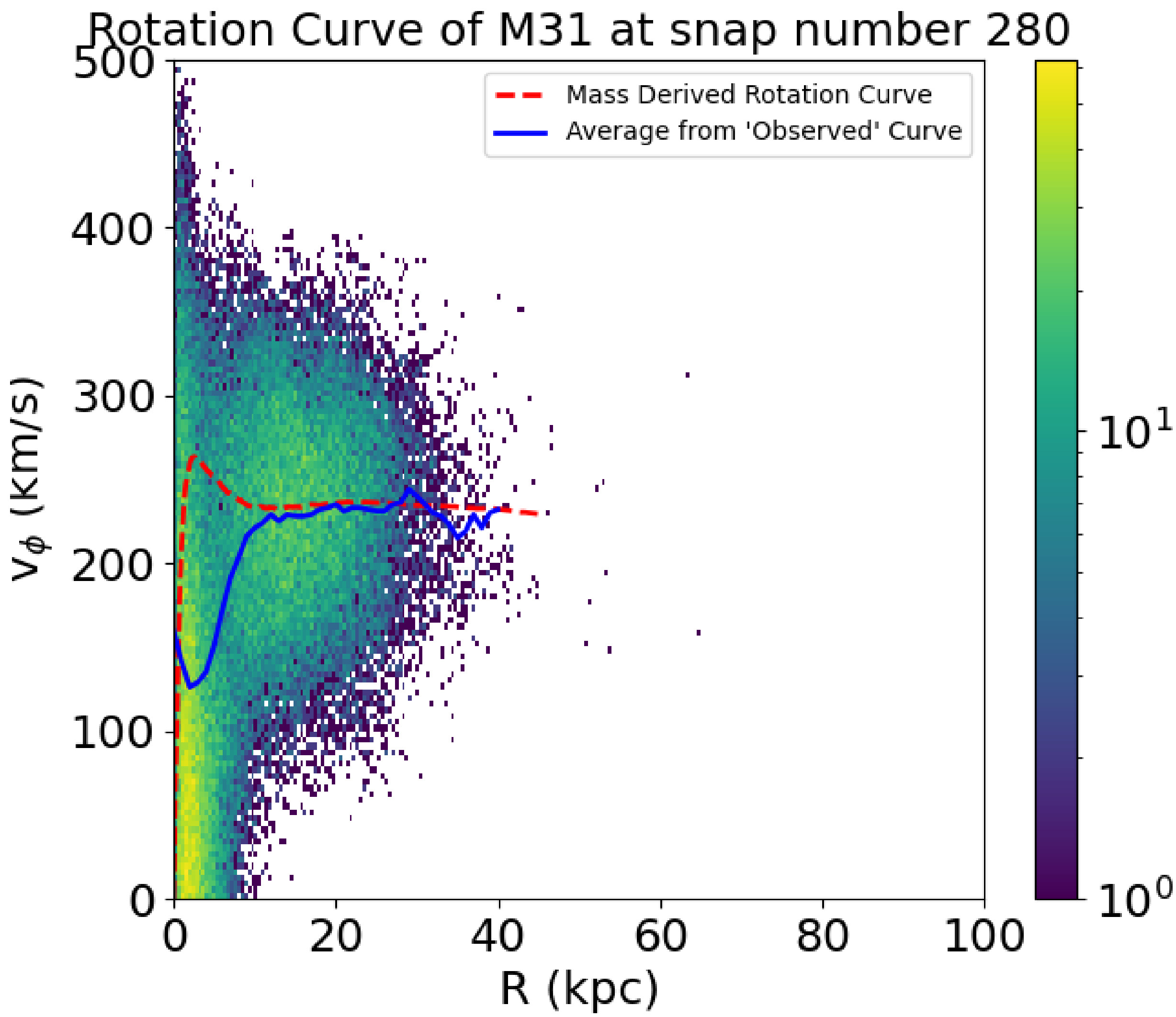

Figure 8. Rotation curve during close encounter.

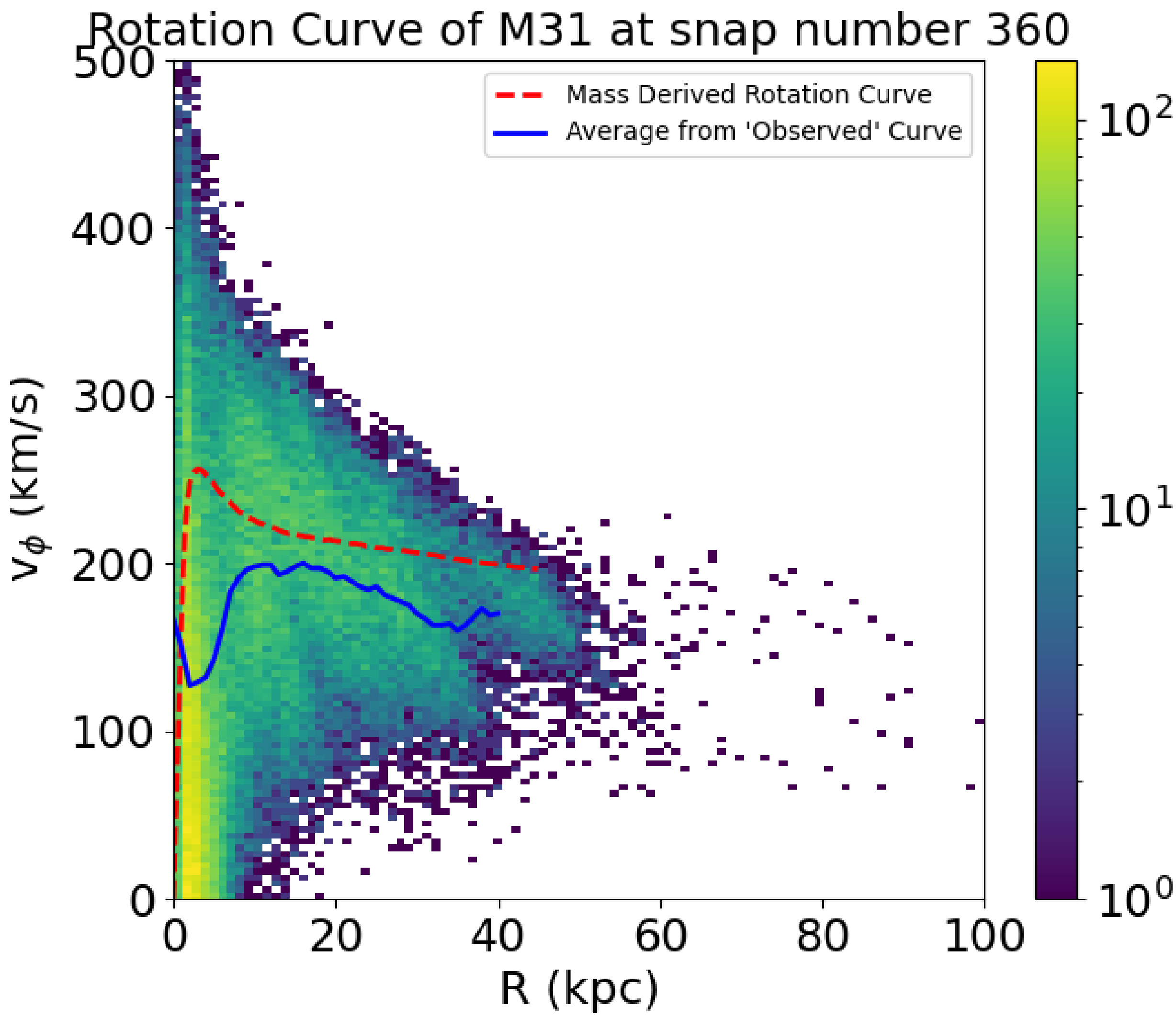

Figure 9. Rotation curve after close encounter.

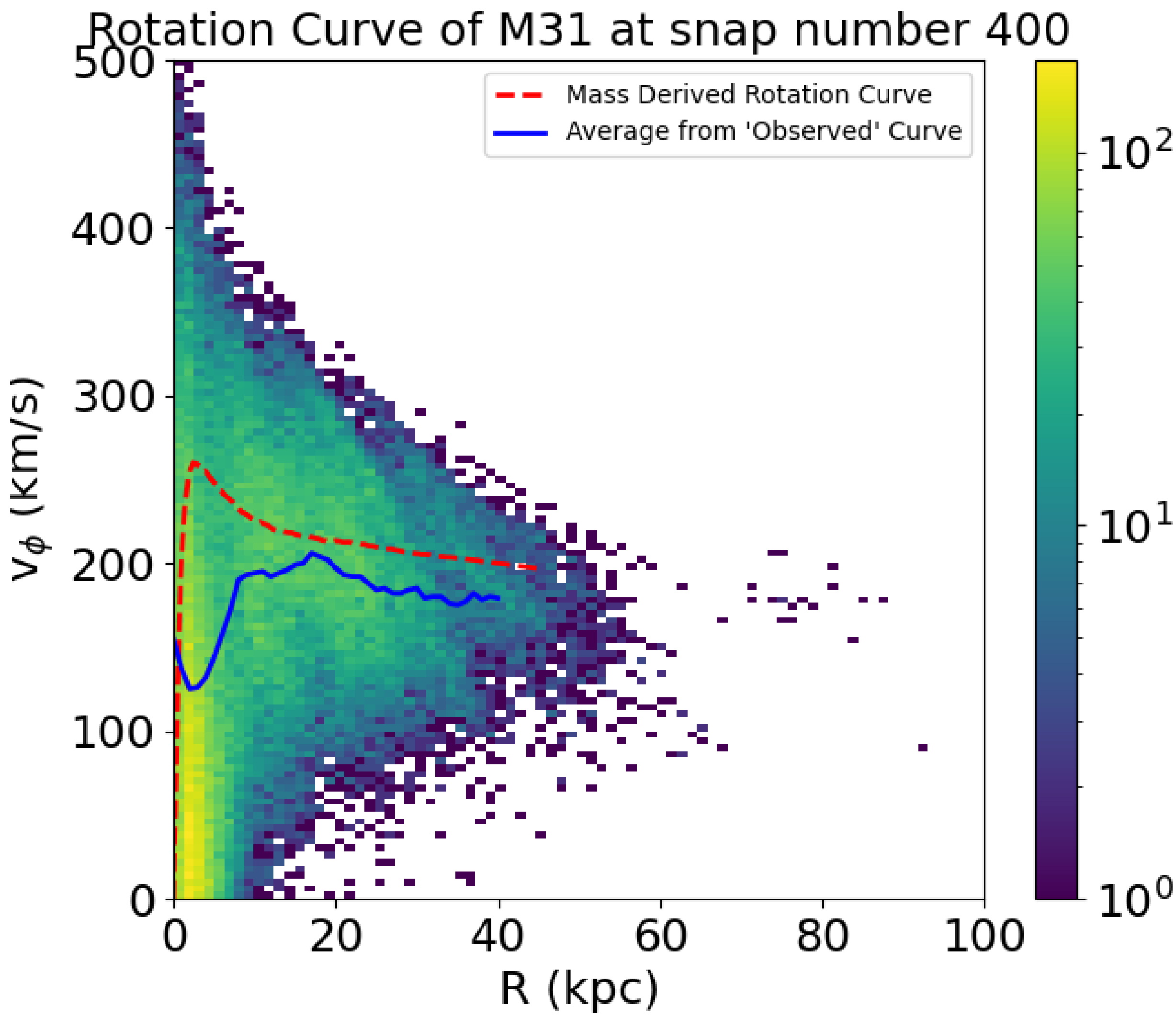

Figure 10. Rotation curves greatly separated from the close encounter.