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MW-M31 Major Galaxy Merger Remnant Rotation Profile

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ABSTRACT

The kinematic evolution in galaxy merger systems reveals the evolution of galaxy, leading to a clear classification of galaxies based on archaeological signatures. Major merger systems play an important role in the understanding of galaxy evolution because mergers are the main driver of morphological transformation. We use collisionless an N-body Simulation to study the stellar kinematics of the Milky-Way (MW) and Andromeda (M31) galaxy merger. One key parameter is the rotation profile V_{max}/σ of galaxy merger remnant, which helps to distinguish between fast or slow rotators, aiding in morphological classification. Our result shows that MW/M31 merger behaves as slow rotator with $V_{max}/\sigma = 0.07$, implying that the remnant can be classified as elliptical galaxy. This suggests major mergers can lead significant transformation in kinematic structure, reinforcing the role of galaxy merger as a key tracer of galactic evolution history.

Keywords: Major Merger — Stellar Disk — Stellar Bulge — Rotation Curve — Velocity Dispersion— Rapid/Slow Rotator

1. INTRODUCTION

Major mergers, direct collisions and gravitational interactions between galaxies of comparable mass, mass ratio of two galaxies less than 1:4, are one of the most significant processes in galaxy evolution, reshaping their structure, kinematics, and morphological identity. In particular, the interactions of stellar disks and stellar bulges during interactions determine whether remnants are rotationally supported or not. **The stellar disks** refer to high density population of stars with ordered rotation, distinguishing them from other parts of galaxy (Bryant & Krabbe 2021). In contrast, **the stellar bulges** are located towards the center, composed of a population of metal-rich stars with higher random motions (**?**). Understanding how these components respond to interaction with other galaxies and evolve their system is essential to depict the archaeological evolution of galaxies. An observationally constrained example of the major merger is the future collision between the Milky Way (MW) and Andromeda (M31), the two dominant galaxies that are well studied.

The study of the kinematics of major mergers remnants provides crucial insight into the galaxy structural formation and galaxy evolution. A **galaxy** is defined as a "gravitationally bound collection of stars whose properties are beyond our explanation on stellar bodies with a combination of baryons and Newtonian gravity alone" (Willman & Strader 2012). **Galaxy evolution** refers to the cosmic scale transformation of galaxies due to internal and external mechanics, such as migration of stars, star formation, and merging with other galaxies. Galaxies that undergo interactions and central nuclei that have coalesced are considered to be merger remnants. **Rotation curve**, defined as "the velocity a test particle would have if it was on a circular orbit in an axially-symmetrized version of a galaxy's mass distribution" (Bovy 2023), brings important aspect of the system: reveals critical information about the underlying mass distribution of the galaxy, including the all gravitational influences of each particles.**Velosity dispersion** σ is a statistical dispersion of velocities from the mean value of it. Angular momentum redistribution determines whether a remnant behaves as **fast rotator**, coherent rotation is retained, or **slow rotator**, where the velocity dispersion dominates over coherent rotation. Understanding this process connects present-day galaxy profiles to their merger history. For the MW/M31 merger, we can model the galaxy merger precisely given detailed observational data, and study their behavior for a better understanding on how the kinematic structure of galaxies evolves over time.

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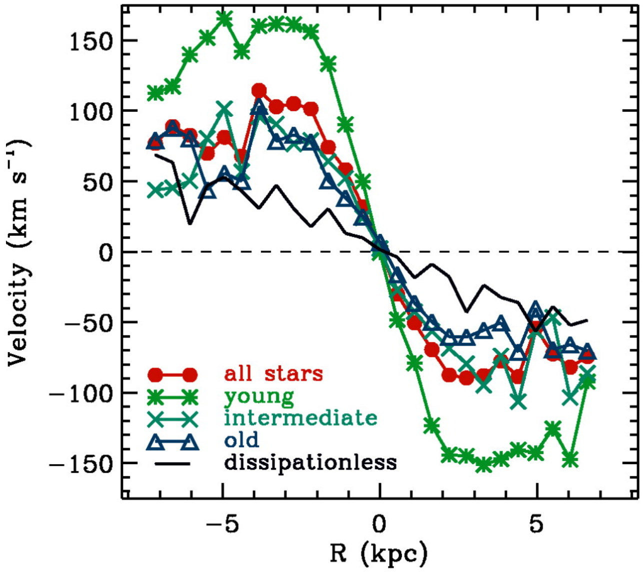

Figure 1. The rotation curve of simulated dissipational major merger remnants, segmented by particle types. The rotational velocity is plotted as a function of radius, adapted from Cox et al. (2006). The figure shows that old stars retain angular momentum the most, dominating the remnant's rotation structure.

Advancements in high-resolution simulations, deep-space observations, and theoretical models have significantly improved our understanding of galaxy evolution. High-resolution imaging from the Hubble Space Telescope (HST) (Meylan et al. 2004) and the James Webb Space Telescope (JWST) (Gardner et al. 2006) have provided insights into the earliest galaxies. Large-scale surveys, such as the Sloan Digital Sky Survey (SDSS) (Kollmeier et al. 2019), have helped identify the classification of galaxy structure. On the theoretical side, large-scale simulations such as EAGLE (Schaye et al. 2015) and IllustrisTNG (Nelson et al. 2021) have improved our ability to model galaxy mergers, gas accretion, and structural transformations. Cox et al. (2006); Naab et al. (2014) used hydrodynamic simulations to show that merger remnants formed by various theoretical galaxies, suggesting that gas-rich major mergers tend to produce fast-rotating remnants, with coherent rotation retained from old systems. Whereas gas-poor mergers or multiple mergers tend to produce slow-rotators.

While these simulations provide strong theoretical studies on future galaxy mergers, key unresolved questions remain: what determines major merger remnants becomes a fast or slow rotator? The MW/M31 system presents an excellent case study to refine our understanding of how major mergers affect galaxy kinematics. By combining observational constraints with detailed numerical simulations such as those simulation (van der Marel et al. 2012), we can develop more precise models of galaxy evolution and rotational transformation.

2. THIS PROJECT

In this paper, we will investigate the kinematic properties of remnants from a future merger between the Milky Way and Andromeda. By focusing on the contribution of the stellar disk component to rotational velocities of the remnants, we will study the emergence of rotational or dispersion-dominated support.

Our study directly addresses the open question of what components contributes to change in rotation properties throughout merger interaction. By analyzing MW/M31 major merger system, we aim to test theoretical predictions based on observational constraints. The MW and M31 contain significant stellar disks and moderate gas contents. With this system, we can explore the future merger system's behavior with specific initial conditions in a kinematic perspective.

3. METHODOLOGY

To study the kinematic properties of the MW/M31 merger remnant, we utilize N-body simulation originally developed by (van der Marel et al. 2012). An N-body simulations solves the gravitational interactions between a set of particles, representing a mass contribution in a galaxy. These simulations solve Newton's gravitational law to provide a theoretical prediction of future positions and velocities of particles in the system.

This work combines individual N-body simulated Low Resolution MW and M31 galaxy data into one dataset, as a remnant. We will analyze the kinematics of the remnant by studying its velocity dispersion using low resolution simulation from 0 Gyrs to 10 Gyrs from the present. We focus on the stellar disk contributions to study the internal dynamics of the remnant. Stellar Bulge and Dark matter contribution are included in the simulation throughout the merger process, however excluded from the analysis on velocities.

To determine the rotation properties of remnants, we begin by combining MW and M31 data into a single dataset. We first recalculate the center of mass of the merged system and shift all particle positions and velocities into this new frame. Next, we compute the total angular momentum and rotate the coordinate system to align the cartesian z-axis with the angular momentum vector, ensuring that the main rotation occurs in x-y plane. The circular velocity V_{circ} at the radial distance r (kpc) away from the center of mass is defined as $V_{circ} = \sqrt{\frac{GM}{r}}$,where M is the Mass of the host galaxy in

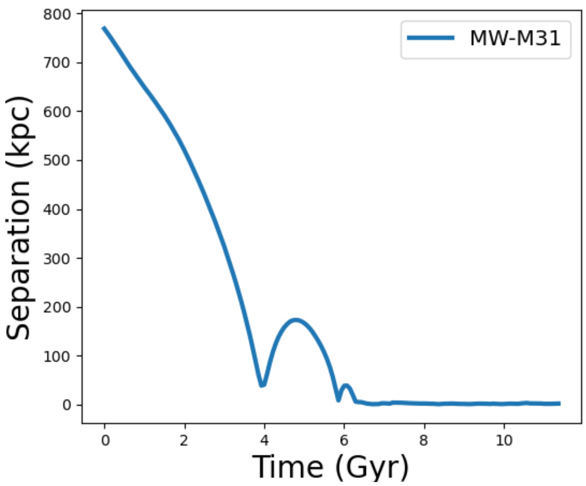

Figure 2. Spatial separation of MW and M31 center of masses as a function of time, measured from the present day. A decreasing trend shows the approach and future direct interaction of two galaxies. Trend converges after 6 Gyrs from the present day, at which the merging process is complete.

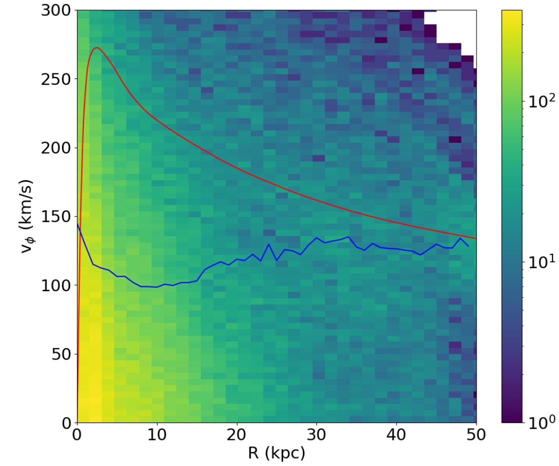

Figure 3. Analytical rotation curve (Red) and circular velocity in cylindrical ϕ direction (Blue) of stellar disks as functions of radial distance from the center of mass at 8 Gyrs from present. Background colors are the 2D histgram of the number of particles at a given radius and rotation velocity.The analytical rotation curve shows more than 100km/s higher at the most discrepant point from the circular velocity curve close to the center of the system. The circular velocity V_ϕ agrees with the histgram, representing the actual motion of each particle. Slower V_ϕ around 5 to 15 kpc indicates the formation of the bar on a non-circular orbit, leading to slower circular velocities of particles near the center. We found V_{max} to be 127, the mean value of V_ϕ at radius from 25 kpc to 50 kpc.

$M_\odot$. We calculate the azimuthal velocity to extract the circular motion of the system. To examine whether the system is the fast or slow rotator, we evaluate the ratio of maximum rotation velocity and the velocity dispersion V_{max}/σ, where V is the maximum center rotational velocity, and σ is the variance of particle azimuthal velocities at each radius. The velocity dispersion σ is calculated with particles within half mass radius r_c, the radius where the half of the mass in the system is located from the center. The variance of the particle velocities:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(v - \langle v\rangle)^2 \tag{1}$$

$$\langle v\rangle = \frac{1}{N}\sum_{j=1}^{N} v_j \tag{2}$$

,where σ is the variance, $\langle v\rangle$ is mean velocity, N is number of particles in simulation, and v is velocity of each particle. We will implement those using `NumPy` functions: `numpy.mean()`, `numpy.std()`.

To visualize the kinematic structure of the remnant, we will generate a figure of the profile of V_{max}/σ as a function of time. This plot will help us to understand the change in velocity profiles as the merger interaction goes on, revealing the ratio between the main coherent rotation of the system and the random motion of each particle. This figure is essential for answering the question of whether the major merger remnant is a fast or slow rotator. A threshold of $V_{max}/\sigma = 0.6$ is commonly used to separate fast and slow rotators Emsellem et al. (2007).

We expect that MW/M31 merger remnant forms a elliptical galaxy with a moderate rate of rotation because MW/M31 merger does not fall firmly into dry or gas-rich merger category.

4. RESULTS

Figure 3 shows the analytical rotation curve and the circular velocity of MW/M31 merger remnant at 8 Gyrs from the present. It is apparent that the rotation speed of the merger remnants varies over the radius from the center of mass. Unlike current MW galaxy rotation, where the center of mass rotates at the slowest speed, this remnant has high rotation. The maximum rotation speed about the major axis was found to be 148 km/s. Notably, V_ϕ remains below V_{circ} at all radii, peaking at approximately 150 km/s at 38 kpc from the center, compared a peak V_{circ} is about 270 km/s at less than 10 kpc from the center.

Figure 4 presents the time evolution of the kinematic support ratio, V_{max}/σ, calculated from 0 Gyrs to 10

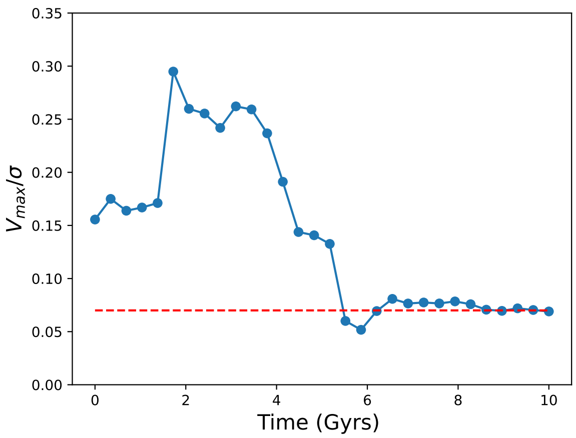

Figure 4. The kinematics of MW/M31 merger remnant. The center velocity dispersion profile, V_{max}/σ, is plotted over time from the present. The trend converge to 0.07 (Red dashed line) at 7 Gyrs, which corresponds to the time when the dynamics of galaxies stabilize. The velocity profile V_{max}/σ is lower than a threshold value 0.6 at all times, concluding to the slow rotator classification of the MW/M31 merger remnant system.

Gyrs. After 6 Gyrs from present, the change in the rotation profile significantly decreased and remained stable thereafter. This timescale corresponds to when the centers of the Milky Way and M31 fully merge and settle into a common potential well.

5. DISCUSSION

The primary result of this study is that the MW–M31 merger remnant reaches a stable kinematic structure by approximately 6 Gyr, with a final V_{max}/σ value of 0.07, classifying it as a slow rotator. This supports the hypothesis that major mergers of spiral galaxies can lead to the formation of dispersion-supported elliptical-like systems.

This result is consistent with previous findings from merger simulations, such as those discussed in (van der Marel et al. 2012), which predict the Milky Way–M31 merger to produce a spheroidal remnant. Our result quantitatively supports this picture by directly evaluating the V_{max}/σ ratio using stellar kinematics. It also aligns with theoretical expectations that major mergers efficiently randomize stellar orbits and destroy disk-like rotation. The conclusion has broader implications for galaxy evolution, reinforcing the paradigm that galactic morphology and kinematics are shaped by major merger events. It suggests that the eventual fate of many spiral galaxies in dense environments may be to evolve into slowly rotating elliptical galaxies as a result of similar collisions.

Uncertainties in this analysis arise from the use of Low Resolution simulation data, which limits spatial resolution and may underestimate small-scale velocity features. Additionally, the assumption of perfect alignment of the angular momentum vector with the z-axis introduces small projection uncertainties. Finally, our analysis focused only on stellar particles and did not account for gas dynamics or feedback processes, which could alter the rotational structure in more realistic simulations. Furthermore, the analysis was restricted to disk components, neglecting contributions from the bulge and halo. This limited focus likely reduced the accuracy of our reconstruction of the remnant's overall structure, especially in regions dominated by non-disk mass components. On the analysis itself, we have determined V_max to be the mean of V_ϕ at radial distance 25kpc to 50 kpc, based on qualitative observation of V_ϕ curve.

6. CONCLUSIONS

The kinematic evolution in galaxy merger systems reveals the evolution of galaxy, leading to a clear classification of galaxies based on archaeological signatures. Major merger systems play an important role in the understanding of galaxy evolution because mergers are the main driver of morphological transformation. We use collisionless an N-body Simulation to study the stellar kinematics of the Milky-Way (MW) and Andromeda (M31) galaxy merger. One key parameter is the rotation profile V_{max}/σ of galaxy merger remnant, which helps to distinguish between fast or slow rotators, aiding in morphological classification.

One key finding from this analysis is that the MW–M31 merger remnant exhibits a V_{max}/σ ratio of only 0.07, firmly classifying it as a slow rotator. This supports the hypothesis that major mergers of disk galaxies, especially those with moderate gas content, tend to form dispersion-dominated, elliptical-like systems. This outcome aligns with prior theoretical predictions and simulations and provides further quantitative evidence that such mergers transform initially rotationally supported galaxies into remnants through angular momentum redistribution and kinematic interaction. It also emphasizes the long-term dynamical impact of major mergers in shaping the kinematic identity of galaxies.

Future directions for this work include expanding the analysis beyond the stellar disk to include contributions from the bulge, halo, and gas components, which were neglected in this study. Incorporating gas dynamics, star formation, and feedback processes could provide a more realistic picture of the post-merger structure. Additionally, higher-resolution simulations would help resolve small-scale kinematic features and better capture the dynamical transitions during merger phases. From a computational perspective, refining the angular momentum alignment algorithm and including a more rigorous treatment of projection effects could improve the accuracy of kinematic measurements. These steps would allow a deeper understanding of how various physical processes and galaxy components collectively determine the final state of merger remnants.

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