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MW-M31 Major Galaxy Merger Remanent Rotation Profile

Hina Suzuki[1,*]

[1] University of Arizona

ABSTRACT

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1. INTRODUCTION

Merger mergers, direct collisions and gravitational interactions between galaxies of comparable mass, 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 determines whether remnants are rotationally supported or dispersion-dominated. The stellar disks refer to high density population of stars with ordered rotation, distinguish them from other part of galaxy. In contrast, the stellar bulges tends to be more spherical, population of stars with higher random motions. Understanding how these components responses to interaction with other galaxies and evolve its system is essential to depict archaeological evolution of galaxies. A observational constrained example of major merger is the future collision between the Milky Way (MW) and Andromeda (M31), the two dominant galaxies that are well studied of.

The study of kinematics of major mergers remnants provide crucial insight into the galaxy structural formation and galaxy evolution. A galaxy is defined as a gravitationally bound collection of starts 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 galaxy due to internal and external mechanics, such as migration of stars, star formations, and merging with other galaxies. Galaxies which undergo interactions and central nuclei have coalesced is consider to be merger remnants. Angular momentum redistribution determines whether a remnant behave as fast rotator, coherent rotation is retained, or slow rotator, where the velocity dispersion dominate over coherent rotation. Understanding this process connects present-day galaxy profiles to their merger history. By studying MW/M31 merger, we can model galaxy merger precisely given detailed observational data, and better understand how kinematic structure of galaxies evolve over time.

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 provides insights into the earliest galaxies. Large-scale surveys, such as the Sloan Digital Sky Survey (SDSS) (Kollmeier et al. 2019), have helped identify 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 cohereant rotation retained from old systems. Whereas gas-poor mergers or multiple mergers tends to produce slow-rotators.

While these simulations provides strong theoretical studies on future galaxy mergers, key unresolved questions remain : what determines a major merger remnants becomes a fast or slow rotator? What components of galaxies, such as gas content, disk masses, and bulge masses, contributes to the resulting kinematic properties? The MW/M31 system presents an excellent case study to refine our understanding of how major mergers affect galaxy kinematics. By combining observational

Email: hinas@arizona.edu
* Steward Observatory and Department of Astronomy
Department of Electrical and Computer Engineering

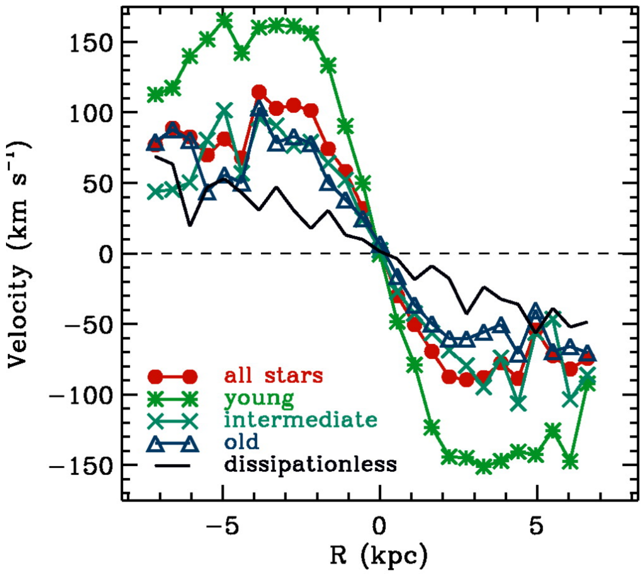

Figure 1. The rotation curve of a simulated disspational major merger remnants, segmented by particle types. The roational velocity is plotted as a function of radius, adapted from Cox et al. (2006). The figure shows that old stars retain angular momentum the most, dominating the remnant's rotation structure.

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 future merger between the Milky Way and Andromeda. By focusing on contribution of stellar disk and stellar bulge components on rotational velocities of the remnants, we will study emergence of rotational or dispersion-dominated support.

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

3. METHODOLOGY

To study the kinematic properties of the MW/M31 merger remnant, we utilize N-body simulations 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 solves Newton's gravitational law to provide 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 remanent. We will analyze the kinematics of the remnant by studying its velocity dispersion by using low resolution simulation at ——- approximately the time when two galaxies completed their merging process and relative velocity has stabilized sufficiently. We focus on stellar disk contribution to study the internal dynamics of the remnant. Dark matter contribution is included in simulation throughout the merger process, however excluded from analysis on velocities.

In order to determine 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 cartesian z-axis with the angular momentum vector, ensuring that the main rotation occurs in x-y plane. We calculate the rotation curve by computing the azimuthal velocity of particles. To examine the system is rotationally supported or not, we evaluate the ratio of maximum rotation velocity and the velocity dispersion, over a range of radius from the center. The velocity dispersion σ is calculated as 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 $(V/\sigma)_{max}$ as a function of radius. This plot will help us to understand velocity profiles as a function of radius, revealing the ratio between main coherent rotation of the system and random motion of each particle. Figure 2 is an example of a plot to be created. This figure is essential for answering the question whether the major merger remnant is a fast or slow rotator. The higher value of the $(V/\sigma)_{max}$ profile would suggest the remnant will be the more rotationally supported, higher density towards the center.

We expect that MW/M31 merger remnant forms a elliptical galaxy with moderate rate of rotation because

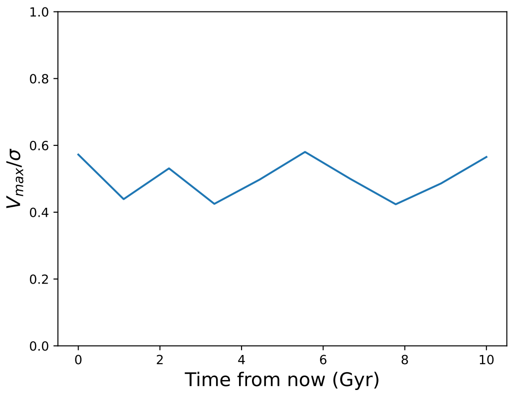

Figure 2. Example of the plot to be made based on analysis. Velocity Dispersion profile $(V/\sigma)_{max}$ as a function of time from present in Gyr.

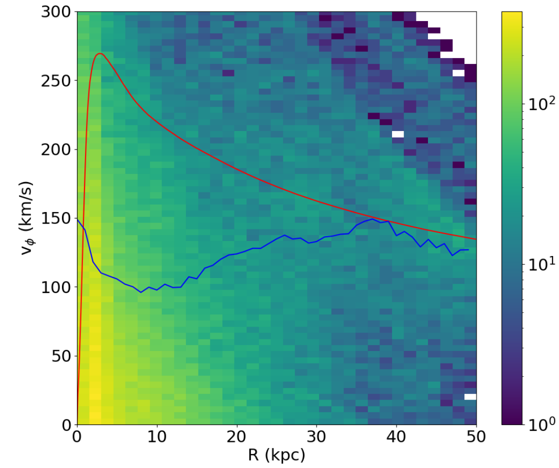

Figure 3. Analytical rotation curve (Red) and circular velocity in cylindrical ϕ direction (Blue) of stellar disks as functions of radial distance from the center of mass at 8 Gyrs from present.

MW/M31 merger does not fall 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 center of mass rotate at the slowest speed, this remnant have high rotation. The maximum rotation speed about 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, $(V/\sigma)_{max}$, calculated from 0 Gyrs to 10 Gyrs. After 6 Gyrs from present, change in the rotation profile significantly decreased and remaining stable thereafter. This timescale corresponds to when the centers of the Milky Way and M31 fully merge and settle into a common potential well.

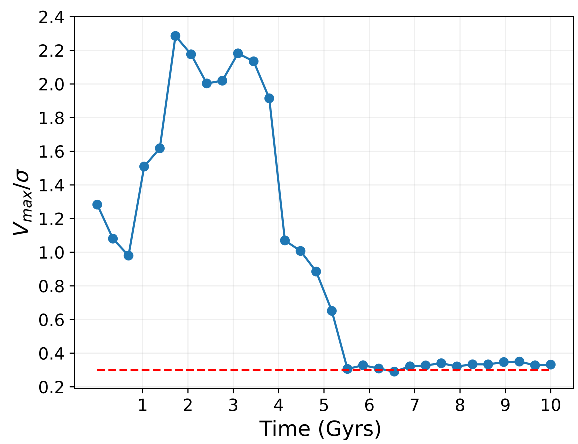

Figure 4. The kinematics of MW/M31 merger remnant. The center velocity dispersion profile, V/σ, is plotted over time from present. You see the trend that it converge to 0.3 after 6 Gyrs, which corresponds to the time when dynamics of galaxies stabilize.

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 $(V/\sigma)_{max}$ value of 0.3, 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 $(V/\sigma)_{max}$ 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.

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