

# Kinematics of the the Merger Remnant

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## ABSTRACT

This paper discusses the kinematics of the merger remnant particularly after a major merger. Studying the resulting stellar kinematics particularly of the bulge and disk components provides valuable insight into the structural evolution of such galaxies. We study the kinematics of MW-M31 using a combination of collisionless N-body simulations and semi-analytic orbit integrations (R. P. van der Marel et al. (2012)). This paper specifically addresses whether the disk is dispersion dominated or rotationally supported after the merger has taken place. Thus, after the merger, the merger remnant is dispersion dominant with the value of  $V/\sigma$  at half-mass radius = 0.235 at 8.57 Gyrs, indicating slow rotator properties. This helps us in understanding how gas rich major mergers from rotationally supported to pressure supported and due to nearly flat velocity dispersion plots, we can infer that it exhibits elliptical galaxy like properties.

**Keywords:** Local Group — Major Merger — Rotation Curve — Velocity Dispersion — Galaxy — Galaxy Evolution — Rapid/Slow Rotator – Dry Merger

## 1. INTRODUCTION

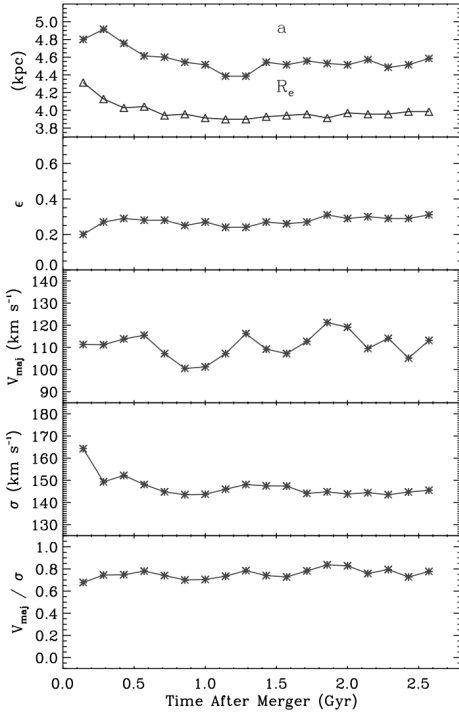
**Local group** consists of the Milky Way (MW) and Andromeda (M31). The Local Group's three most massive members are all spiral galaxies: the Milky Way (MW), Andromeda (M31), and Triangulum (M33), with their masses in a ratio of  $\sim 10:10:1$ . Local Group, which contains more than 80 galaxies and has a total mass of roughly  $3.5 \times 10^{12} M_{\odot}$  (R. E. González et al. (2014)). They are on a collision course and will have their closest approach in about 4.3 Gyrs and a series of close approaches later. The future evolution of the Local Group is primarily shaped by the major merger between MW and M31. A **major merger** is when merger where the ratio of the stellar masses of the progenitors are 1:3 or greater. Studing the kinematics of such merger remnants will help us to placing the Local Group in the broader context of galaxy formation and evolution. A major merger refers to the gravitational collision and subsequent combination of two galaxies of roughly equal size and mass. The study of these major mergers can help us to understand the place of the Local Group in the cosmic evolution and can help us to further our understanding of the properties of cold dark matter. DM Halos gravitationally attract baryons. Therefore, they are the sites of galaxy formation.

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 (B. Willman & J. Strader (2012)). **Galaxy evolution** is the process by which galaxies change over time. By investigating the stellar kinematics in simulated MW/M31 merger remnants, we can better constrain the physical mechanisms responsible for shaping the morphological and dynamical outcomes of major mergers like MW-M31. The MW-M31 merger is expected to result in a transition from two well-structured spiral galaxies to a more spheroidal or elliptical remnant (A. Toomre & J. Toomre (1972)). However recent studies have showed that disc galaxies could also be created from a major merger. Studying the resulting stellar kinematics for instance if they are fast or slow rotators, particularly of the bulge and disk components provides valuable insight into the structural evolution of such galaxies **Rapid rotators** are rotation supported early type galaxies with disc like kinematics while **slow rotators** are dispersion supported with little or no global rotation.

The merger between MW and M31 has a closest approach of  $31.0^{+38.0}_{-19.8}$  kpc (R. P. van der Marel et al. (2012)). The resulting merger remnant will likely resemble an elliptical galaxy. M33 is expected to settle into orbit around the remnant, although there are non-negligible probabilities of a direct hit with the MW or even ejection from the Local Group (R. P. van der Marel et al. (2012)). The figure above illustrates the kinematic

signatures of merger remnants, showing how properties such as ellipticity, and rotation vary with time. This supports findings from simulations where dissipational (gas-rich) mergers produce more oblate, rotating, and isotropic remnants, matching observed features of low-luminosity elliptical galaxies (T. J. Cox et al. 2006).



**Figure 1.** Time evolution of structural and kinematic properties of a major merger remnant: semimajor axis  $a$ , half-mass radius  $R_e$ , ellipticity  $\epsilon$ , major axis rotation speed  $V_{\text{maj}}$ , velocity dispersion  $\sigma$ , and the ratio  $V_{\text{maj}}/\sigma$ . Based on simulations of identical disk galaxy mergers, relevant to MW–M31 remnant studies. Adapted from T. J. Cox et al. (2006). Settled dynamically within  $\sim 1$  Gyr. Retained some disk-like features (moderate ellipticity, nonzero  $V/\sigma$ ).  $V/\sigma$  stays between  $\sim 0.6$  and  $\sim 0.75$ , with a mild increasing trend. Thus, system is pressure supported (elliptical-like)

Despite considerable progress in understanding the MW–M31 merger, several important questions remain open. Simulations show that gas-rich mergers produce more rotationally supported, isotropic remnants, while dry mergers result in slowly rotating, anisotropic systems (T. J. Cox et al. (2006)). However, it is still unclear which specific combination of gas content, orbital geometry, and feedback processes will dominate in the actual MW–M31 event. ((R. P. van der Marel et al. 2012)). Addressing these questions requires high-resolution simulations. My project specifically contributes to this effort by analyzing the expected kinematic profiles of the MW–M31 merger remnant using outputs from such sim-

ulations (R. P. van der Marel et al. (2012)), to better constrain its future rotational support and velocity dispersions. The **velocity dispersion** is the statistical dispersion of velocities about the mean velocity for a group of astronomical objects( Wikipedia contributors (2025a)).

## 2. THIS PROJECT

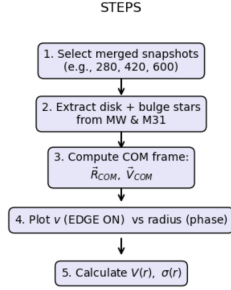
The topic of this project is Stellar disk/bulge kinematics after a major merger. I would be particularly looking at the evolution of the rotation curve. The **rotation curve** of a disc galaxy is a plot of the orbital speeds of visible stars or gas in that galaxy as a function of their radial distance from that galaxy’s centre ( Wikipedia contributors (2025b)) The “observed” rotation curve and the mass-derived rotation curve based on the enclosed mass profile would be compared which will offer insights into how well observational proxies trace underlying mass distributions after a merger. Furthermore, the project aims to analyze the velocity dispersion components of the stellar populations in both the disk regions.

The open question of whether the gas rich merger as opposed to dry merger is more rotationally supported or is pressure supported will be understood by this project. A merger between gas poor galaxies is called **dry merger**. We will also come to know the sense of rotation that this merger remnant exhibits post merger.

Understanding post-merger stellar kinematics is crucial to advancing our knowledge of galaxy evolution. The kinematics of merger remnants affect where they lie on the Tully–Fisher and Fundamental Plane. By comparing these results with observations, we can answer whether such remnants preserve rotational properties or rapidly settle into isotropic, pressure-supported systems which will tell us about fate of the MW–M31 remnant, Local group and the general formation knowledge of early-type galaxies.

## 3. METHODOLOGY

An N-body simulation refers to a computational technique in which the motion of a large number of particles is calculated by numerically solving their mutual gravitational interactions over time. The N-Body simulation used here is by R. P. van der Marel et al. (2012). They conducted collisionless N-body simulations of the MW–M31–M33 system, modeling the gravitational interactions between stars and dark matter components. The simulations were carried out using the GADGET-3 code. In the simulations, the dark halo of each galaxy was represented by Hernquist density profile (L. Hernquist (1990)).



**Figure 2.** Steps to the project. The half mass radius method was adapted from T. J. Cox et al. (2006)

To study the kinematics of the merger remnant, I will first identify simulation snapshots where the MW and M31 have fully merged and the system is dynamically relaxed. These snapshots will be the separation plots in Homework 6. Using the formula  $(SN * 10)/0.7$ , I found out the snapshots numbers to be 280, 420 and 600. I will use high res as it would give me much better velocity dispersions as a function of  $r$ . Stellar particles belonging to the disk and bulge components of both the MW and M31 were extracted and combined into a single dataset representing the stellar body of the remnant. The center-of-mass (COM) position and velocity were computed using mass-weighted averages:

$$\mathbf{R}_{\text{COM}} = \frac{\sum m_i \mathbf{r}_i}{\sum m_i}, \quad \mathbf{V}_{\text{COM}} = \frac{\sum m_i \mathbf{v}_i}{\sum m_i}, \quad (1)$$

where  $m_i$ ,  $\mathbf{r}_i$ , and  $\mathbf{v}_i$  are the mass, position, and velocity of each stellar particle. All particle coordinates were shifted into the COM frame using:

$$\mathbf{r}'_i = \mathbf{r}_i - \mathbf{R}_{\text{COM}}, \quad \mathbf{v}'_i = \mathbf{v}_i - \mathbf{V}_{\text{COM}}. \quad (2)$$

To study rotational structure, the system was reoriented so that the net angular momentum vector lies along the  $z$ -axis, aligning the stellar disk (if present) in the  $xy$ -plane. A phase-space diagram plotting the velocity  $V$  against radius was constructed to visually identify rotation trends. This diagram was color-coded to show direction of motion and extended to 10–15 kpc to encompass any outer rotational features, consistent with methods from Lab 7.

Rotational support was quantified by computing both the “observed” rotation curve, defined by the mean  $V$  in radial bins, and the theoretical circular speed:

$$V_c(r) = \sqrt{\frac{GM(< r)}{r}}, \quad (3)$$

where  $G$  is the gravitational constant,  $M(< r)$  is the mass enclosed within radius  $r$ , and  $r$  is the radius in

kiloparsecs. This comparison reveals the extent to which the remnant is rotationally or pressure-supported. The cylindrical velocity was calculated as follows, (Both the  $r$  and velocity components were normalized and then used in this equation)

$$v_\phi = \frac{xv_y - yv_x}{\sqrt{x^2 + y^2}} \quad (4)$$

The velocity dispersion (standard deviation) in the azimuthal direction is:

$$\sigma_\phi(R_i) = \sqrt{\frac{1}{N_i} \sum_{j=1}^{N_i} (v_{\phi,j} - V_\phi(R_i))^2} \quad (5)$$

The velocity dispersion profile was calculated in radial bins, especially within the half-mass radius, to trace how random motions vary with radius. An important thing to note here is that only the disk particles were taken into consideration while computing the half mass radius. The half-mass radius  $R_{\text{half}}$  is defined such that,

$$\sum_{i: R_i < R_{\text{half}}} m_i = \frac{1}{2} \sum_i m_i$$

To evaluate rotational support at the half-mass radius  $R_{1/2}$ , we compute,

$$\left(\frac{V}{\sigma}\right)_{R_{1/2}} = \frac{V_\phi(R_{1/2})}{\sigma_\phi(R \leq R_{1/2})} \quad (6)$$

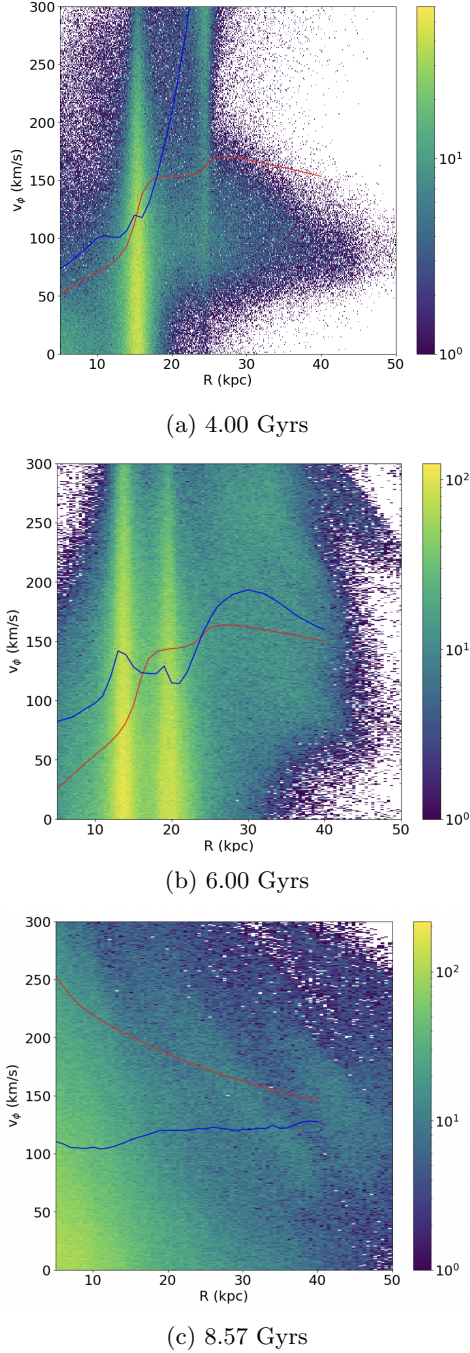
Then, the ratio  $V/\sigma$  will be plotted as a function of radius. Regions where  $\max(\frac{V}{\sigma}) \gg 1$  indicate disk-like fast rotators, whereas values of  $(\frac{V}{\sigma}) \ll 1$  correspond to pressure-supported ellipticals.

Plots of the rotation curves, dispersion profile, and  $V_\phi$  phase diagram, were plotted.

The MW/M31 merger remnant after complete merger might exhibit dispersion support. Low velocity dispersion is expected due to random stellar motions which would lead to slow rotations which would be similar to elliptical galaxies.

## 4. RESULTS

Figure 4 shows the evolution of the  $V/\sigma$  profile for the merger remnant at three different times alongside the expected circular velocity for an edge-on orientation. At 4.00 Gyrs, the  $V_\phi$  traces the red curve of circular velocity (from the enclosed mass) agrees with the blue observed mean  $V_\phi$  in the inner regions of the disk. At 6 Gyrs, we can see a structure starting to form. At 8.57 Gyr, the blue curve is significantly lower than the theoretical circular velocity which indicates that it has formed an elliptical form of a structure. The speeds remain



**Figure 3.** This is the  $V_\phi$  plotted as a function of radius in the merger remnant at 4.00, 6.00 and 8.57 Gyr (left to right) and the theoretical circular velocity of the merger remnant edge on (red line) and the blue line which is the mean  $V_\phi$  going out in radial bins. When the merger started, at 4 Gyrs the circular velocity curve derived from enclosed mass seem to trace the mean  $V_\phi$  in the inner disks indicating that it is rotation supported which also indicates of two merging cores. In the outer disk, they show a strong deviation from the theoretical circular velocity. At 6 Gyrs, most stars have merged into one system. There is still some deviation present from the theoretical circular velocity, some regions are rotation dominated while others pressure dominated. At 8.57 Gyrs, we see that the theoretical circular velocity does not trace the  $V_\phi$  at all. Thus, this is a direct evidence that the speeds remain roughly constant from the center outward, indicating a slow rotator. This suggests the system is dispersion dominated and elliptical.

roughly constant as a function of radius which indicates that there is not much rotation component remaining in the structure and is majorly dominated by dispersion. Thus, it indicates that the structure resembles an elliptical galaxy.

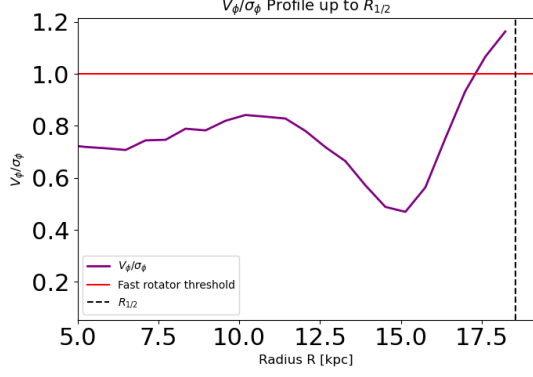
Figure 4 shows the evolution of the velocity dispersion as a function of radius over the course of the MW-M31 merger. At 4 Gyrs, the merger is still going on, so as we move towards different values of  $r$ , there is a strong variation which indicates that there are some regions that are dispersion supported while there are others which are rotation supported. At 6 Gyrs, the parts which are merged in the inner disk regions show low velocity dispersion and the outer regions are rotationally supported. At 8.57 Gyrs, we see that the majority of the galaxy (within half mass radius) is dispersion supported. The low  $V/\sigma$  value of 0.235 confirms that random stellar motions dominate the central regions. These decreasing values show that, the rotationally supported into dispersion supported after the merger has happened.

## 5. DISCUSSION

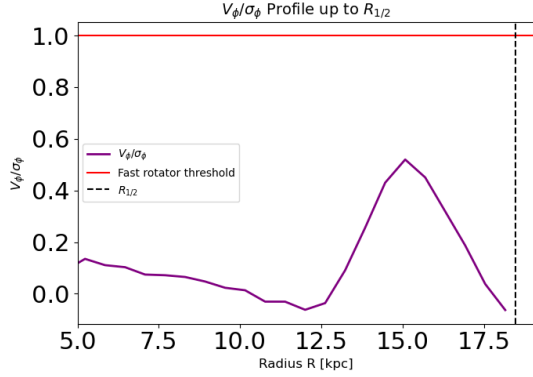
The main takeaway from this paper is that after the merger has happened, the merger remnant is pressure supported. Yes, the result agrees with my hypothesis. The MW- M31 merger is expected to result in a transition from two well-structured spiral galaxies to a more spheroidal or elliptical remnant (A. Toomre & J. Toomre (1972)). Thus, our result supports this expectation. Understanding this relation between the observed mean  $V_\phi$  vs  $r$  and theoretical circular velocity vs  $r$  tells us whether such remnants preserve rotational properties or rapidly settle into isotropic, pressure-supported systems which will tell us about fate of the MW-M31 remnant, Local group and the general formation knowledge of early-type galaxies. We also saw that the galaxy is dispersion dominated from being rotation supported during the course of its merger. The  $V/\sigma$  at half mass radius at 8.57 Gyrs was 0.235. This hints at the fact that is a slow rotator and would exhibit elliptical galaxy like properties.

It was expected to result in a transition from two well-structured spiral galaxies to a more spheroidal or elliptical remnant (A. Toomre & J. Toomre (1972)), thus agreeing with literature. This result can be further generalized to suggest that galaxies in dense environments may also evolve into dispersion dominated systems as a result of undergoing similar collisions or interactions.

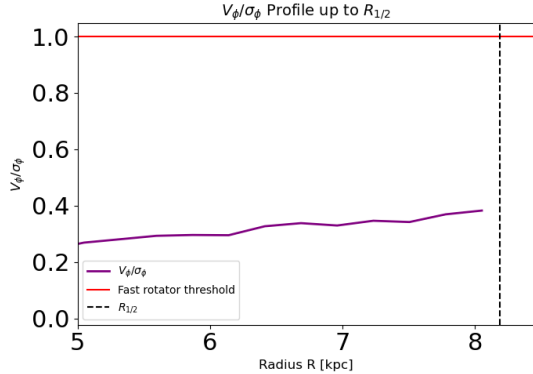
An important point to note is that all the plots in this paper have an  $x$  limit (left) to 5 kpc. This is because there is a smoothening length (R. P. van der Marel et al. (2012)).



(a) 4.00 Gyrs,  $V_\phi/\sigma$  at half-mass radius = 1.265



(b) 6.00 Gyrs,  $V_\phi/\sigma$  at half-mass radius = 0.343



(c) 8.57 Gyrs,  $V_\phi/\sigma$  at half-mass radius = 0.235

**Figure 4.** Evolution of the  $V/\sigma$  profile as a function of radius at three different stages of the galaxy merger: (a) 4.00 Gyrs, (b) 6.00 Gyrs, and (c) 8.57 Gyrs. The red dashed line indicates the threshold  $V/\sigma = 1$ , above which a galaxy is considered a fast rotator. At 4 Gyrs, the system shows peaks in the outskirts, indicating local rotation-dominated regions due to merging substructures on the outside. By 6 Gyrs, a more coherent rotation pattern emerges at larger radii, but the inner regions remain dispersion-dominated. At 8.57 Gyrs, the system settles into a more stable configuration with low  $V/\sigma$  throughout, which hints at a transition to a dispersion-supported remnant. Thus, after the merger, the merger remnant is dispersion dominant and slow rotator with the value of  $V_\phi/\sigma$  at half-mass radius = 0.235.

The theoretical circular velocity can be model dependent. Also, I used the half mass radius to filter out the  $v_\phi$ . Also, I took the radius upto 41 kpc. It might not have included some points which could have made the results slightly different. Some of the physics, such as stellar and AGN feedback are not fully captured by the  $V/\sigma$  measurement of the merger remnant.

## 6. CONCLUSION

This paper discusses the kinematics of the merger remnant particularly after a major merger. Studying the resulting stellar kinematics particularly of the bulge and disk components provides valuable insight into the structural evolution of such galaxies. We study the kinematics of MW-M31 using a combination of collisionless N-body simulations and semi-analytic orbit integrations (R. P. van der Marel et al. (2012)). This paper specifically addresses whether the disk is dispersion dominated or rotationally supported after the merger has taken place. The main finding from this paper is that after the merger of M31-MW, the merger remnant is dispersion dominant, most likely a slow rotator with the value of  $V/\sigma$  at half-mass radius = 0.235 at 8.57 Gyrs, using the simulation data. This supports the hypothesis. Major mergers are primary drivers of galactic morphological and kinematic transformation in galaxy evolution. The outcome is a slowly rotating elliptical remnant that can be broadly applied to all gas rich mergers involving galaxies with comparable mass and structure to the Milky Way and M31. We have not included any feedback processes, which could be included in future work. Also, only the disk components were used to calculate the velocity dispersions. Thus, in the future, the gas and bulge components could also be included to study their effects.

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