Draft version May 1, 2020
Typeset using LaTeX **twocolumn** style in AASTeX63

The kinematics of the stellar disk particles in the MW/M31 galaxy major merger remnant

Madison Walder

(Received March 24, 2020)

Keywords: Galaxy Merger, Major Merger, Merger Remnant, Velocity Dispersion, Rapid/Slow Rotator

1. INTRODUCTION

As is well known throughout the astronomy community, The Milky Way (MW) and Andromeda (M31) are set on a course to collide in a spectacular galaxy merger event ~4-5 billion years from now (van der Marel et al. 2012). This galaxy merger is classified as a major merger given that the colliding spiral galaxies have approximately the same mass. Luckily, we can determine what this collision will look like and how the aftermath (i.e. the merger remnant) will behave dynamically through simulations. Specifically, they allow for the analysis of the stellar kinematics of the remnant. The stellar remnant's kinematical properties such as its velocity dispersion σ, the spread of velocities around the average velocity of the stars, can allow for the determination of whether the remnant will be a fast or slow rotator. A fast rotator is defined as a system where velocity and dispersion are quite similar (V/$\sigma \rightarrow 1$), whereas a slow rotator is a system that is dispersion dominated (V/σ <0.6).

Analyzing the stellar kinematics of a major merger remnant is incredibly important to our understanding of galaxies and galaxy evolution. A galaxy is defined by Willman & Strader (2012) as: *A gravitationally bound set of stars whose properties cannot be explained by the combination of baryons and Newton's laws of gravity.* Galaxy evolution is the study of how galactic properties (such as the stars, morphology, internal kinematics, black hole, gas content etc.) change over time. A major merger event of two spiral (late-type) galaxies such as that of the MW and M31 will drastically alter the galactic properties of both galaxies, especially their internal kinematics. Generally, early-type galaxies (ellipticals) have more random stellar motions whereas the stars of late-type galaxies (spirals) have more structured rotational motions. Depending on the type of binary merger event, like whether it is a "wet" merger (the coalescence of two gas-rich spiral galaxies) or "dry" merger (the coalescence of two gas-poor galaxies), the kinematics of the merger remnant can have numerous possibilities. A wet merger can supply the amount of gas needed to conserve the angular momentum of the system for the remnant to have a significant amount of rotation. It also is currently believed to lead to the formation of low luminosity ellipticals. However, the kinematics of a dry merger event (such as the MW/M31 collision) are not believed to be the same.

Since the MW/M31 merger will be "dry", it is theorized that the collision will increase the velocity dispersion of the system and the remnant will not have the gas needed to conserve angular momentum. A current dominating theory for wet mergers is referred to as the "merger hypothesis", which states that the merging of two equal-mass, gas rich spiral galaxies forms an elliptical galaxy (Toomre & Toomre 1972). This is supported by Cox et al. (2006) who used numerical simulations to study the kinematics of major merger events between gas-rich and gas-poor mergers (referred to as dissipational and dissipationless respectively in the paper). As shown in Figure 1, they found that the simulations of gas-rich major mergers with masses 20 times smaller or 30 times larger than $\sim 10^{12} M_{\odot}$ successfully replicated the observed kinematic properties of more massive ellipticals. As shown in Figure 1, they found that the simulations of gas-rich remnants successfully replicated the observed kinematic properties elliptical galaxies, while gas-poor remnants did not.

Many of the open questions in this field have to do with the accuracy of the "merger hypothesis" predicting the correct formation of ellipticals, as well as the uncertainty of the outcome of a dry merger event. For example, one thing that the merger hypothesis does not account for is what happens to a galaxy's dark matter halo during a merger event. Romanowsky et al. (2003) simulated a lack of a dark matter halo to match the velocity dispersion profiles observed in some intermediate luminosity ellipticals. As for the uncertainty of the remnant of a dry merger, there is a particular focus on

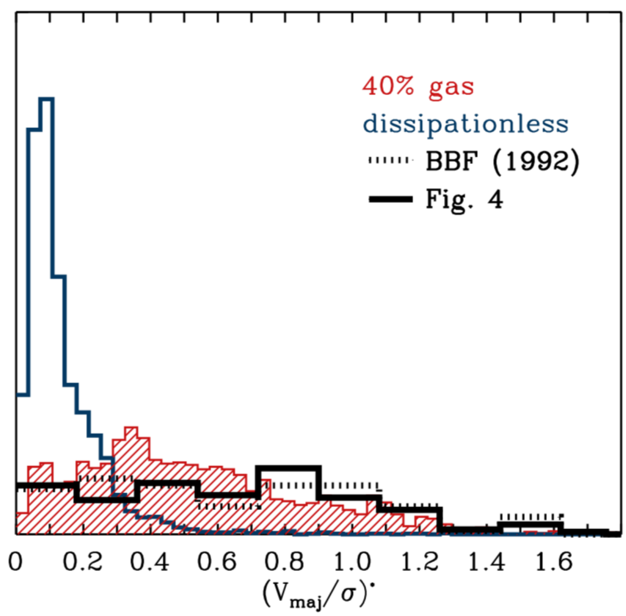

Figure 1. Histogram of (V/σ) for both gas-poor (blue) and gas-rich (red) remnant simulations overplotted with data from observed ellipticals and spheroids (black). The red and black histograms are much more similar than the blue one, thus supporting that the simulations of the gas-rich mergers better emulated the stellar motions of ellipticals. (Cox et al. 2006).

the outcome of the Milky Way and M31 merger. Some open questions in the field are: *What will the Milky Way and M31 remnant look like? Will it form an elliptical, or something entirely different?* and *How will the merger remnant behave kinematically?* Currently, astrophysicists attempt to answer these questions through numerical integration simulations to allow us to "see" into the future of the system after the collision. These simulations include assumptions of physics that follow Newton's laws of gravity as well as Cold Dark Matter Theory (the theory that dark matter only interacts with matter gravitationally).

2. THIS PROJECT

This paper will be focusing on some specific aspects of the stellar kinematics after the MW and M31 have coalesced, specifically at Snapshot 800 which is ~12 Gyr from now, and well after the two galaxies have merged. I plan on using simulation data to determine whether the remnant is rotating, as well as whether the remnant will be a fast or slow rotator. The stellar kinematics to be analyzed will be the average velocity of particles as a function of position, as well as the dispersion of the velocities as a function of position.

Following the description above, I plan to address how the stellar merger remnant will behave kinematically in this project, specifically in terms of velocity dispersion and rotation. I also plan to address whether it will behave like a classic elliptical.

In terms of galaxy evolution, studying how the merger remnant behaves kinematically after the galaxies have become one allows us to take into account that the interactions of galaxies with each other can drastically change the morphology and dynamics of each. This study will help lessen the uncertainty surrounding the outcome of a dry merger event, like whether the remnant is rotating, and if it is rotation or dispersion dominated like ellipticals.

3. METHODOLOGY

The simulation data used in this paper was generated by van der Marel et al. (2012) who used it to determine the velocity vector of M31 with respect to the Milky Way. One part of their project was using an N-body model, a simulation of the motions of N particles under the influence of gravity in this case, to simulate the internal mechanics of M31. They used their simulation to determine the trajectory and behaviors of the MW, M31, and M33.

I will determine whether the remnant is rotating by orienting the remnant so that its angular momentum vector is along the z direction, then creating a phase diagram to analyze the out-of-page velocity component along each axis. I will also determine whether it is a fast or slow rotator by calculating the (V/σ) ratio along a given axis for the remnant, where V is the average velocity along that axis. Figure 2 shows a phase diagram of the velocity component oriented out of the page vs. a position axis for the Milky Way at Snapshot 000.

The code first orients the remnant so that its angular momentum vector is along the z-axis using the RotateFrame function from Lab 7. The code then uses the VelocityMeansandDispersions function to calculate the average out of page velocity:

$$\bar{V} = \sum_{i=1}^{N} \frac{V_i}{N} \tag{1}$$

along an axis where $_i$ is the out of page velocity for the i-th disk star within a cube of dimensions dx, dy, dz along the specified axis and N is the total number of disk stars within the cube. Then it calculates the dispersion about that velocity in all 3 dimensions (σ_x, σ_y, σ_z):

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - \bar{V})^2} \tag{2}$$

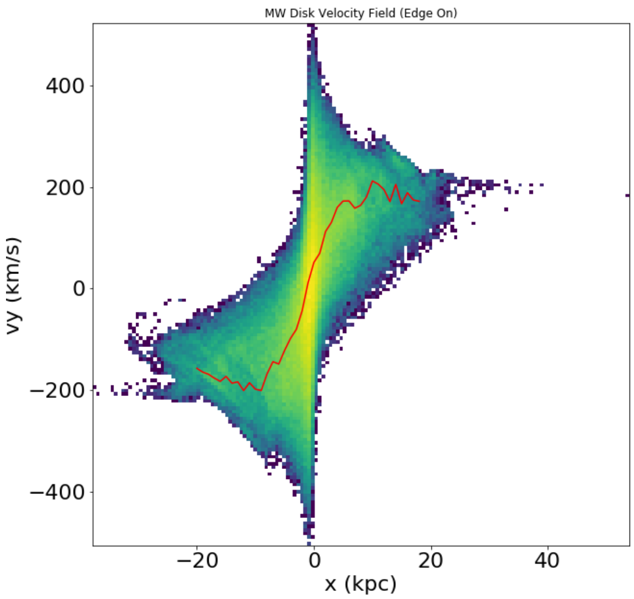

Figure 2. Phase diagram of MW's y-component of velocity vs. x-component of position. You can determine the mean velocity (shown in red) and the velocity dispersion along the axis using a diagram like this. There is clearly rotation here since the velocity has two very prominent positive and negative velocity peaks.

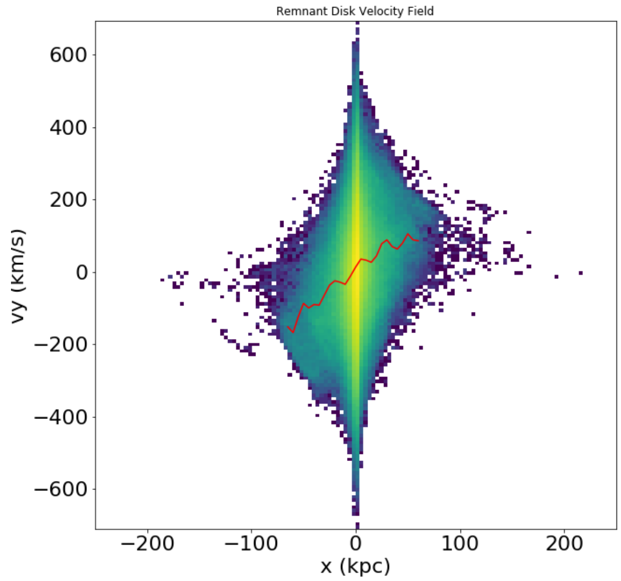

Figure 3. Phase diagram of the MW/M31 remnant's y-component of velocity in (km/s) vs. x-component of position in kpc. The mean velocity along the axis is overplotted in red. The average velocity $\bar{V_y}$ peaks above and below zero, meaning that the remnant is rotating about the z-axis.

and stores all calculated quantities in arrays as output. It then calculates the ratio of $\frac{\bar{V_{perp}}}{\sigma_{perp}}$ and $\frac{\bar{V_{perp}}}{\sigma_{tot}}$ where $\bar{V_{perp}}$ is the average of the out of page velocity component, σ_{perp} is the component dispersion around the average out of page velocity, and σ_t is the total 3D dispersion about that velocity. It then finds the maximum velocity value of the average velocity array and takes the ratio of that value with its corresponding dispersion to get the ratio that determines whether the remnant is rotation or dispersion dominated.

One of the plots created will be a phase diagram of V_y vs x with the $\bar{V_y}$ as a function of x plotted on top to determine if the remnant is rotating. If it is, the average velocity will be higher than zero on one side and lower than zero on the other. The other plots that will be created are $\frac{\bar{V_y}}{\sigma_y}$ vs x and $\frac{\bar{V_y}}{\sigma_{tot}}$. This will be used to show whether the remnant is dispersion dominated and if it is a fast or slow rotator.

I believe that the MW/M31 remnant will be rotating since both the MW and M31 have their own angular momentum, then there is no possible way it will be devoid of angular momentum. As for the classification of whether the remnant will be a fast or slow rotator, I believe that it will be a slow rotator since the merger between M31 and the MW will have very little gas.

4. RESULTS

Figure 3 shows a phase diagram of the remnant's V_y component along the x axis with the average $\bar{V_y}$ as a function of x plotted on top, much like that of the Milky Way in Figure 2. Though it is not quite as prominent as the peaks seen in Figure 2, the mean velocity along the x-axis in the remnant has a peak above and below zero. This tells us that the remnant is in fact rotating about the z-axis.

Figure 4 shows the ratio of the average V_y over σ_y and average V_y over σ_{tot} along the x-axis. There is a negative and positive peak that is not $\sim$0 in the ratio in both plots, further confirming that remnant is rotating. This also implies that the remnant is not only rotating, but its rotation dominates its dispersion.

5. DISCUSSION

The stellar disk remnant of the MW and M31 major merger will be rotating well after the event occurs, thus agreeing with the initial hypothesis. It is theorized that the Milky Way and Andromeda merger will yield a giant elliptical galaxy. The motions of stars in classic ellipticals are quite randomized with no structured rotation,

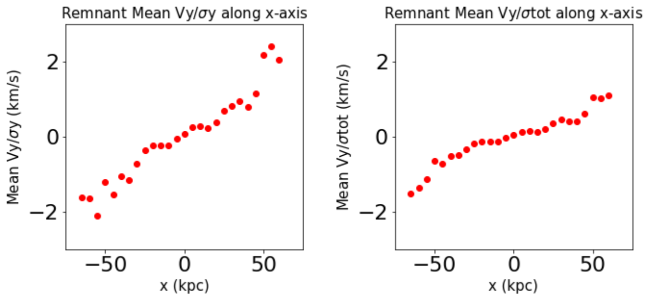

Figure 4. The left panel is a diagram of the MW/M31 remnant's $\frac{\bar{V_y}}{\sigma_y}$ ratio vs. x-component of position in kpc. The right panel is a diagram of the MW/M31 remnant's $\frac{\bar{V_y}}{\sigma_{tot}}$ ratio vs. x-component of position in kpc. The remnant does not seem to be dispersion dominated since the V/σ ratio is not close to zero along the entire x axis.

i.e. they do not generally rotate. However, according to Figure 3 the remnant will have some rotation around an axis. This tells us that the aftermath of a dry major merger like MW/M31 may not lead to a classic giant elliptical, but perhaps something else.

REFERENCES

Cox, T. J., Dutta, S. N., Di Matteo, T., et al. 2006, ApJ, 650, 791, doi: 10.1086/507474

Romanowsky, A. J., Douglas, N. G., Arnaboldi, M., et al. 2003, Science, 301, 1696, doi: 10.1126/science.1087441

Toomre, A., & Toomre, J. 1972, ApJ, 178, 623, doi: 10.1086/151823

van der Marel, R. P., Fardal, M., Besla, G., et al. 2012, ApJ, 753, 8, doi: 10.1088/0004-637X/753/1/8

Willman, B., & Strader, J. 2012, AJ, 144, 76, doi: 10.1088/0004-6256/144/3/76