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# EVOLUTION OF THE KINEMATICS OF MW/M31 BULGES DURING AND AFTER THE MERGER

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## ABSTRACT

Understanding the evolution in dynamical processes during galaxy mergers is a key to comprehend galactic evolution. In this paper, I study the kinematic evolution of the bulge components and the dynamical stability of the merger remnant of the MW-M31-M33 system by analyzing $N$-Body simulation data. The bulge component is embedded in the innermost regions of a galaxy which becomes difficult to study due to the disk component with respect to its orientation across our line of sight. I find the system is dynamically stable with a high mass concentration found at radii $r < 5$ kpc and is supported by the Virial Theorem and Jean's equation. The kinematics of M31 is affected more than MW but follow similar trends in their velocity and mass profiles. The Bulge of the remnant supports a skewed Gaussian distribution with a dispersion value of $\sigma = 111.72$ km s$^{-1}$ and supports a classical bulge when fitted with a Sersic Profile with an index $n = 4$.

*Keywords:* galactic evolution: mergers — local group: MW, M31, M33

## 1. INTRODUCTION

It is still unclear whether merger events between two disk galaxies are responsible for the formation of an elliptical galaxy. Using a cosmic simulation helps us observe and understand the underlining physics of two or more galaxy interactions over long timescales. From these simulations, we can compare them to observations and test whether current theories hold true. (Zepf 1997) suggests two processes in which elliptical galaxies form: either through mergers, two or more colliding galaxies, or caused by star-formation burst surrounded by dust. The more highly recognized scenario is that ellipticals form from mergers which (Kormendy *et al.* 2009) verifies, and (Querejeta *et al.* 2015) conclude that merger events of spirals result in S0 types. However, the process of how galaxies form and evolve over is still open for debate. Observations of spiral galaxies such as MW and M31 have three unique components: the bulge, disk, and halo. The disk and halo components are the most easy to observe. The disk resembles a spiral structure that extends from the center outward. A plethora of gas and dust is found within the spiral arms. Highly active star-formation occurs in this area resulting in young, blue stars, which makes the arms so bright. The halo surrounds spiral galaxies and is associated with older populations of stars and tenuous gas is observed. The bulge is located at the center of the galaxy where it is often obscured by dust and gas from the disk base on the orientation of the galaxy with respect to the line of sight from Earth. However, the bulge of a galaxy can be studied indirectly using $N$-Body simulations.

The bulge of a galaxy is classified as a classical or a pseudobulge. A Classical Bulge has properties of spherical symmetry that are supported by dispersion , which when fitted to a Sersic Profiles with indices $n \geq 2$. Pseudobulges support values $n < 2$ and have boxy or peanut like morphology. Understanding how bulge's dynamics change over time and through mergers can impact our understanding of galactic evolution and the formation of early-type galaxies or that the bulge is the sole responsibility why we observe these type of galaxies. Understanding galaxy evolution through mergers is crucial to strengthen our theories of the formation of early-type galaxies. In particular, studying the kinematics of the bulges between two colliding galaxies is ideal to determine whether the bulge component is responsible for the formation of early-type galaxies that are observed.

## 2. THIS PROJECT

For this project, I will analyze the MW-M31 merger and determine how the bulges of the systems are affected during and after the merger and test the remnant for dynamical stability. Because the bulge lies at the center of a galaxy, the gravitational potential energy is stronger compared to the other components. This means that bulges should undergo the least amount of change compared to its counterparts. But the results may vary depending on overall size and mass of the two colliding galaxies. We know from simulations that mergers are violent interactions that change the galaxies morphology each encounter resulting in instability. It is worth examining how the bulge component of each galaxy, as well as the remnant, are affected and show stability.

## 3. METHODS

### 3.1. *N-Body Simulation*

A collisionless $N$-body simulation is used to explore the MW-M31-M33 system where various initial conditions are chosen for the galaxies. The initial conditions for the disk and bulge components are based on the literature, while the halos are given by Hernquirst profiles. This simulation excluded the effects of gas, allowing high-quality data, and starts at today's time and integrate forward in time $\tau < 12$ Gyr. (Van Der Marel *et al.* 2012)

### 3.2. *My Code*

For this paper, I developed a code to find a snapshot of the particles kinematics pertaining to a specific time that one may want to analyze. Also, algorithms were developed to produce velocity and mass profiles. The Virial Theorem and Jean's Equations are used to test the stability of the MW-M31 remnant. A Sersic profile is used to determine if the remnant has a classical or pseudobulge.

## 4. RESULTS

Four distinct snapshots are used to analyze the evolution of the bulges of the MW-M31 system. These snapshots correspond to times: 0, 4.79, 6.07, and 10.3 Gyr. Time 0 Gyr refers to the state at which the MW is observed today. It will be used as a standard reference to study how the bulge kinematics change over time from its initial conditions. Times 4.79 Gyr and 6.07 Gyr represent the instances where both MW and M31 are at maximum separation. These times were selected because a state of equilibrium is achieved after first and second interactions respectively. The MW and M31 merge sometime at $\tau \gtrsim 6.5$ Gyr. Time 10.3 Gyr is selected to allow the time to equilibrate after the merger.

### 4.1. *Mass and Velocity Profiles*

Bulge particles of MW and M31 within the inner regions at radii < 5 kpc were redistributed at later times before the two merges as seen in Figure 1. MW and M31 mass profiles show a small perturbation throughout the entire process. But at time $\tau = 6.07$ Gyr suggest that that the M31 bulge particles are significantly more affected than then the particles of MW. During the first interaction, there is almost no change in mass distribution but both of the velocity profiles show an overall decrease and causes their peak velocity to occur at a larger radius. A transfer of energy exchange between the two resulted in the particle's orbits to increase. However, M31 could have transferred some kinetic energy to M33 which may explain the significant decrease. After the second interaction, a change in mass distribution becomes more distinct in both galaxies. The exchange of energy between the galaxies cause particles to progress to larger orbits and disperse. The total mass of both systems remains constant which means that the particles remained bound to their nucleus even when they merge.

After the merger takes place at $\tau = 10.3$ Gyr, both MW and M31 particles were examined separately to determine how each galaxy contributes to the remnant, see Figure 2. I found that the remnant particles mass distribution become localized about the center where the remnant is similar to the initial states of both galaxies but with a total mass of $2.9 \times 10^{10} M_{\odot}$

### 4.2. *Sersic Profile*

A Sersic profile fitting was done on the Remnant to identify whether the bulge resemble a classical or pseudobulge, following the equation

$$I(r) = I_0 exp[A(\frac{r}{r_0})^{-n} - B] \tag{1}$$

where $I_0$, $A$, $B$, and $n$ are free parameters, and $r_0$ is taken to be the effective radius $R_{eff}$ and $I_0$ is the central intensity that corresponds to come mass-to-light ration $M/L$.

An attempt to use the python package, *Emcee* to fitting a Sersic Profile to constraint Sersic index $n$ but failed It returned extreme values of $n \geq 15$, and $M/L = 5$. These values were ignored and proposed to have no significance fundamentally. From this failed attempt it resulted in fitting to be done by hand. The table below

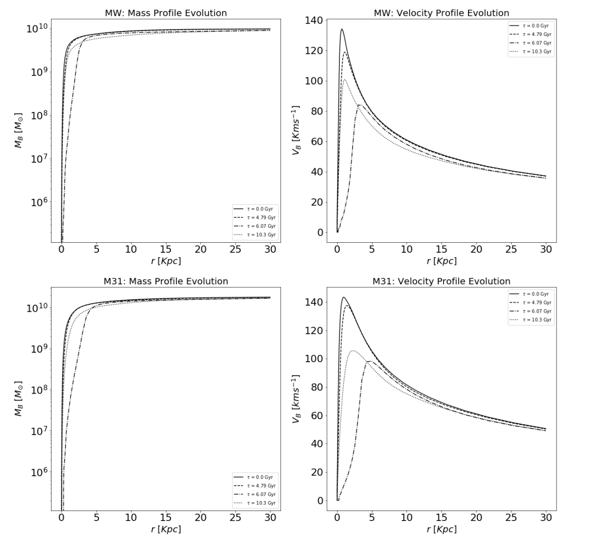


**Figure 1.** Left column shows Mass Profiles and right columns shows Velocity Profiles at four distinct times that occur at before the merger, post first interaction, post second interaction, and Remnant

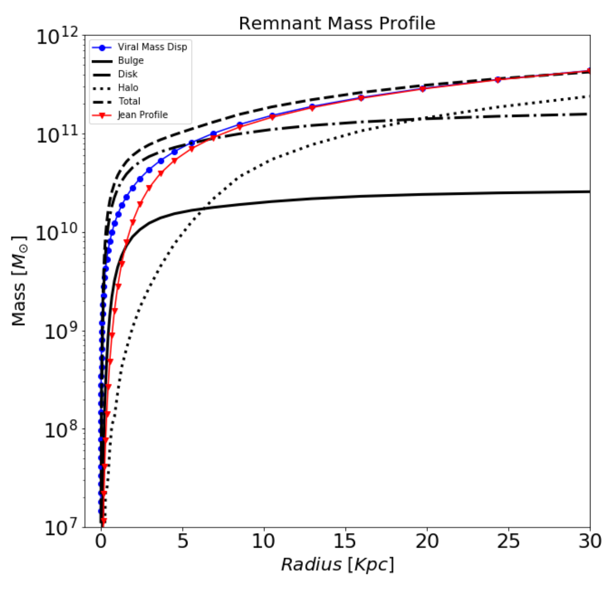


**Figure 2.** This plot show the Mass Profile all of the components along side the $Virial$ and $Jean's Profiles$, where the Bulge components is represented as the solid line.

shows that values that we find that best fit the data to a Sersic Profile assuming spherical symmetry(Also see figure 3).

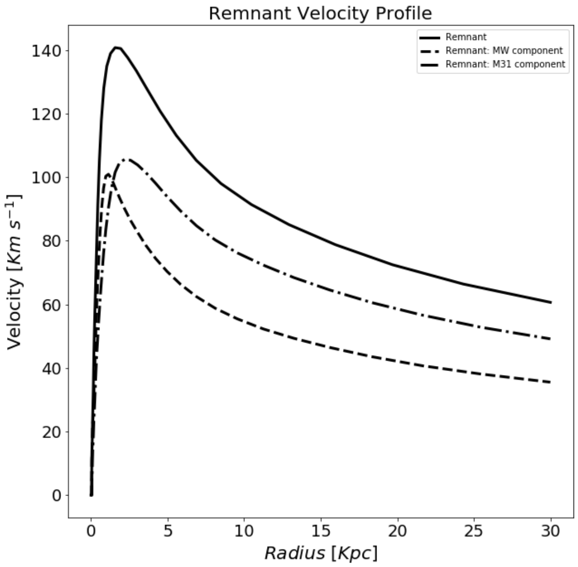


**Figure 3.** Remnant Velocity Profile along with the individual contribution of MW and M31 particles of bulge component.

| Parameter | Value |
|---|---|
| $I_0$ | $1.23 \times 10^8 L_\odot$ |
| $R_{eff}$ | 2.17 [kpc] |
| $A$ | 7.9 |
| $B$ | 1 |
| $n$ | 4 |
| $M/L$ | 2.2 |

A half light radius is calculated and found to be 2.17 [*kpc*] and is adopted as the effective radius for the Sersic model. A mass-to-light ratio of 2.2 is assumed base on the results from William Lake. The $B$ parameter result in best fits when $B = 1$.

### 4.3. *Virial Stability*

Instabilities are a natural consequence of the merging process between galaxies. As MW and M31 became entangled, it is important to analyze whether the remnant achieves a state of equilibrium. Thus, the newly formed system must satisfy the virial theorem. The virial theorem is expressed as:

$$2KE = U \tag{2}$$

$$M_{viral}(r) = f\frac{rv(r)}{G} = f\frac{r\sigma}{G} \tag{3}$$

where $f$ is a scaling factor, $r$ is the distance from the center, and $\sigma$ is the velocity dispersion of the system. The bulge of the remnant does support dispersion. However, the velocity distribution of the bulge is asymmetric Gaussian distribution. It is more practical to use the median of skewed velocity distribution and find the remnant velocity dispersion $\sigma = 111.72$ km s$^{-1}$. A scale factor $f = 5$ is found that fits the virial profile eq. (3) to our data.

I also adopted Jeans equation from (Walker *et al.* 2009) to use to compare our results (see figure 2).

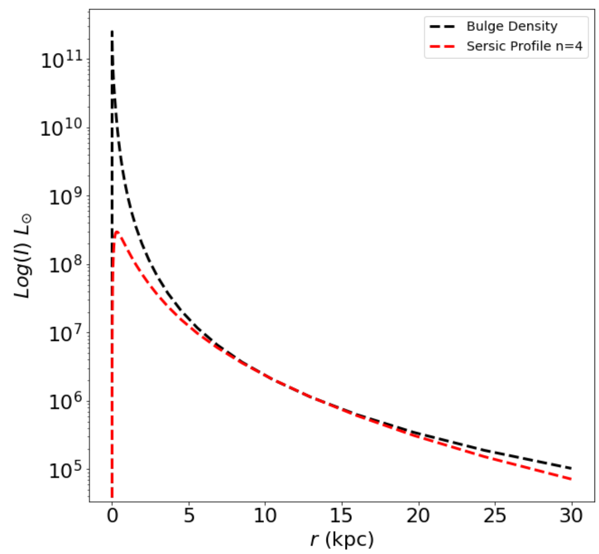


**Figure 4.** Surface Brightness Profile of MW-M31 Remnant with a fitted Sersic Profile of $n = 4$

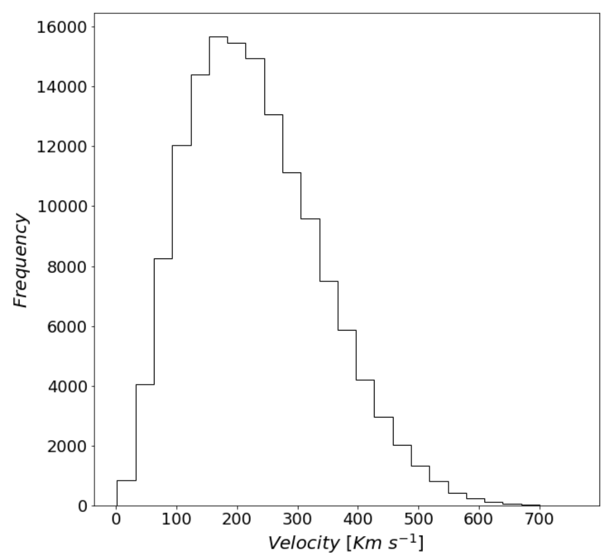


**Figure 5.** Skewed guassian velocity distribution of the renmant's bulge

$$M(r) = \frac{5r_{half}\sigma^2(\frac{r}{r_{half}})^3}{G[1+(\frac{r}{r_{half}})^2]} \tag{4}$$

I find that the system is dynamically stable and is supported by the Virial Theorem and Jean's Equation. However, the data suggests that there is an excess of mass in the innermost regions. Particles at radii $r < 10$ kpc suggest the presence of another mechanism contributing to the overabundance of mass. Further analysis is required to explain why this occurs and what is actually happening.

## 5. DISCUSSION

Before the formation of the Remnant, the bulge component of both galaxies is perturbed by their first encounter, resulting in the systems early instabilities. During their second interaction, I identified an altered structure to their mass and velocity profiles, where I assume that the particle near the center are being strongly distorted by both galaxies center of mass as they begin to merge. Once MW and M31 merged, the remnant's mass and velocity profile look identical to MW and M31 profiles before the merger. The Bulge components of both galaxies are altered over time even though the no drastic changes occur in both the morphology and the overall dynamics of the system. Even though particles contained in the bulge are more gravitationally bounded by their nucleus, it's unlikely to develop significant changes compared to the disk and halo particles, which are more susceptible to decoupling from their system and exchanged particles between colliding galaxies.

A Sersic Index of $n = 4$ indicates that the bulge of the Remnant follows the brightness profile of that of an elliptical galaxy with a classical bulge and is found during the fitting. Visual inspection of remnant found elliptical symmetry that is dispersion supported.

## 6. CONCLUSION

In this paper, I find that the remnant of the MW-M31 system contains a classical bulge that is supported dispersion indicated by the Sersic index. Both the bulge component follow similar trends throughout the merger process where M31 displays a higher deviation of broadening in both mass and velocity profiles. This implies that some other mechanism causes M31 to be affected more than the MW. Lastly, the remnant is found to be stable and is supported by Virial Theorem and Jean's Equation, supported by two different profiles.

### 6.1. *Future Direction*

An adequate study on the morphology of the bulge component of the MW-M31 remnant should be pursued to determine whether bulge growth occurs and how this growth is effected over time. In this study, I have neglected any effects from M33 and should take into account that how the remnant is affected the by dwarf galaxy as it continues to fall in toward the remnant.

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