Draft version April 29, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

Properties of Bulge and Disk Particles in the Milky Way and M31 Merger Remnant

Ellen Jesina[1]

[1] *The University of Arizona*
Tucson, AZ 85719

(Received April 29, 2025)

Keywords: Major Merger, Stellar Bulge, Stellar Disk, Local Group, Elliptical Galaxy

1. INTRODUCTION

Galaxies have been observed to merge across the Universe, and the closest merger to Earth will involve our very own galaxy and Andromeda, or M31. These galaxies, along with the Triangulum Galaxy (M33), make up the local group that is used to refer to the closest galaxies to Earth and the Milky Way. Eventually, the Milky Way and M31 will collide (Cox & Loeb (2008)) which will change the shape and dynamics of the remnant of the merger. In order to better understand how these dynamics have changed, we must observe how the stellar bulge and the stellar disk will change. The stellar bulge is the bright stellar structure that is close to the center of the galaxy, which is commonly surrounding a black hole. The stellar disk involves the stars that are surrounding the center, though at a much farther distance and less concentrated than the stellar bulge, and can often be seen in a spiral pattern for the Milky Way. As the galaxies merge, these components will change in dynamics and relations which can be anticipated by analyzing the merger remnant through coding simulations.

This topic is important to understanding how galaxies evolve as they merge overall. The term **galaxy** is defined as "a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity" (Willman & Strader (2012)).The galaxies undergo evolution through time. **Galaxy Evolution** is overall dependent on the initial conditions such as temperature and gas mixtures, star formation history, and the gravity interactions between baryonic and dark matter (Matteucci (2003)). By studying galactic evolution, we can determine many interactions, including which particles are more likely to be dynamically changed. Furthermore, studying our own galaxy's evolution can offer us insight into its fate and enable us to better understand its interactions with other galaxies. This can even include how this can impact our own Solar System, since it is likely that this event will occur within the Sun's lifetime (Cox & Loeb (2008)). In our case, we are looking into how the remnant of this merger behaves. This remnant, or what is left and formed after the two galaxies merge, is important to understand how different particles behave and evolve so we can understand galactic dynamics more thoroughly. Galaxy mergers are important to study in order to better understand the evolution of galaxies we can observe. The analysis of one or the other can be easily applied to both areas so that we understand galactic dynamics and how the universe has formed as a whole.

It is commonly understood that the Milky Way and Andromeda will eventually merge due to their gravitational attraction. This is expected to happen in the next 5 Gyr (Cox & Loeb (2008)) and can be seen in Figure 1. Galaxy mergers are dependent not only on the mass of the galaxies merging (Lotz et al. (2010)), but also on the amount of angular momentum (Hopkins et al. (2008)). It can even depend on the baryonic mass in particular (Lotz et al. (2010)), though this is more variable when it comes to smaller galaxy mergers as compared to large galaxies like the Milky Way and Andromeda. Recent research has studied the timescales of this merger (Cox & Loeb (2008)), though the explicit dynamics of how our own galaxy will evolve is limited in literature. Much of our understanding comes from how we observe other galaxies merge, visually and dynamically.

Open questions relating to this topic typically revolve around the desire to better understand how the merger remnant would compare to other galactic merger remnants that we can observe. This particularly pertains to the shape of the galaxy remnant and its luminosity. The shape is expected to be elliptical (Cox & Loeb (2008)) and the luminosity is expected to be moderate from recent assumptions, but further modeling can confirm if this is the future fate of our galaxy. There are

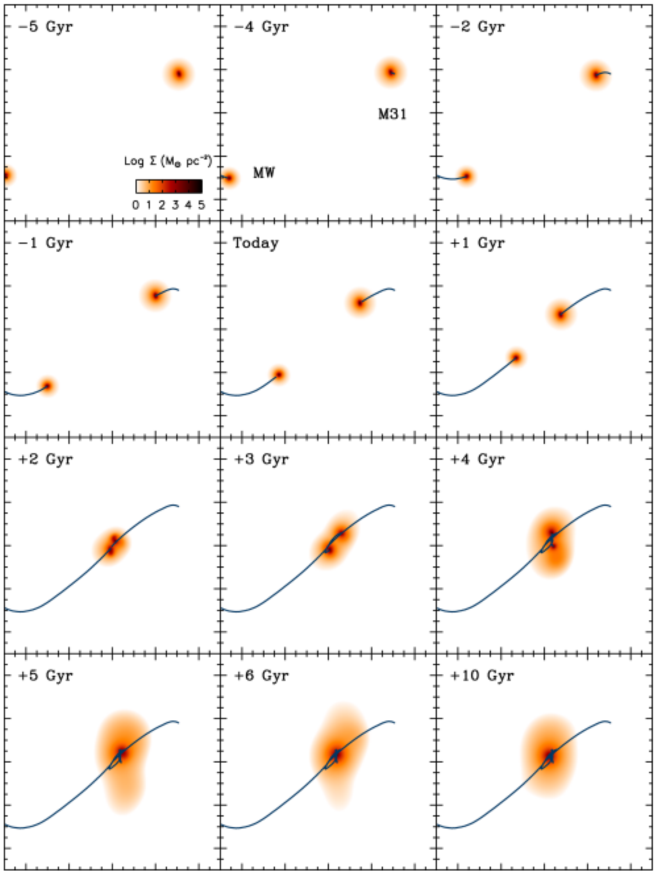

Figure 1. Taken from Cox & Loeb (2008) Projected stellar density throughout the merger of Andromeda (starting in the upper right) and the Milky Way. It is projected to take approximately 5 Gyr from today.

also several questions about how this merger event and its remnant could have an impact on our own Solar System. For example, there is the likelihood of the Sun being absorbed by Andromeda during a close pass-by (Cox & Loeb (2008)), and the possibility of part of the merger being visible to future humans. These questions could be constrained through future modeling, but they may also have to wait until our galaxy advances further in its own evolution.

Further unanswered questions pertain to what the angular momentum is of a galaxy merger remnant. This question was called ambiguous by Hopkins et al. (2008), since it somewhat depends on circular and orbital frequencies of the galaxies merging. There are also only certain angular momenta that are believed to enable galaxies to merge (Hopkins et al. (2008)), otherwise there may be not enough momentum to merge, resulting in very gradual tidal accretion. Looking into the angular momentum of the resulting merger can offer insight into the general momentum required to merge and can explain even black hole dynamics when merging, as initially investigated by Hopkins et al. (2008). This unanswered question is aimed to be better understood through this research.

2. THIS PROJECT

In this paper, we will study how the bulge and the disk of both the Milky Way and M31 evolve after the merger. This will be done through by measuring the mass as a function of radius from the new center of mass. This data will be used in conjunction with velocity as a function of distance from the center of mass to determine the angular momentum of the system.

The main question answered in this paper is: How do the bulge and disk of the galaxy remnant contribute to various aspects of the merger remnant? These various aspects include the mass profile, the overall shape, the velocity dispersion, and the overall angular momentum, the last of which will be investigated by this research directly. Researching the angular momentum of the merger remnant will help answer the angular momentum question previously discussed as being open-ended and not explicitly understood.

Researching this topic is important to gain insight into what parts of the galactic remnant are rotating. Understanding rotation requires an understanding of the aforementioned angular momentum and velocity dispersion, as we need to determine if it is conserved through such a large event such as a galactic merger. We must also determine if there are rotating particles in the remnant so that we can understand the merger's evolutionary history and investigate how initial and final angular momentum affect the merger and its remnants.

3. METHODOLOGY

The primary coding simulation being used is the Center of Mass developed by Dr. Besla . This code evaluates over a set number of snapshots that correlate directly the points of time, either in the past or future, allowing us to model how both the Milky Way and M31 evolve throughout the merger. It follows every particle depending on if they are classified as a stellar disk, stellar bulge, or dark matter halo particle. The Milky Way and M31 will have such powerful interactions that M33 does not need to be explicitly taken into account in this scenario. We will be using the Low Resolution files for this work since we are considering the more general case rather than calculating specific values.

To accomplish this, we must first find the snapshot at which the two galaxies are seen to merge. This has been measured to be around 5 Gyr in the future (Cox & Loeb (2008)), which correlates to a snapshot number around

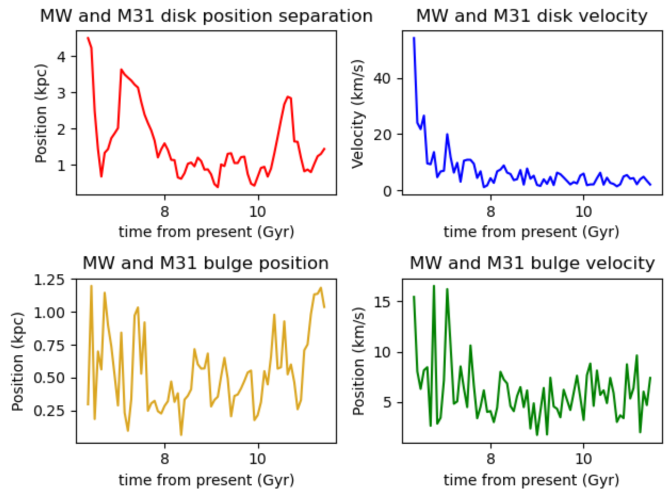

Figure 2. The differences in positions and velocities between the Milky Way and M31 in 5 Gyr and beyond, after they have merged. The separation between the disk and bulge of both of these galaxies is low (<5 kpc) and consistent through time, showing they have merged. Also shown is the difference in velocities of the bulge and disk through time, which is relatively consistent in time. The relatively large disk velocity difference will be explained further later in this paper. Overall, the low differences in position and velocity show that snapshot 445 is an appropriate starting point to analyze the merger remnant.

445. This starting point ensures that snapshots beyond that represents the movement of particles in the merger remnant. The difference in positions and velocities of the bulge and disk can be seen more clearly in Figure 2; since the separations at the start are consistent through time. From here, we can determine the mass and velocity from this snapshot forward (). The distance from the center of mass will be given by a standard numpy array. The mass, in conjunction with this radius, will enable calculation of the mass profile. We can further use the radius with the velocity to determine velocity dispersion and angular momentum. These results will then be plotted against each other, or against time, to show the merger remnant's evolution. This outline can be seen more clearly in Figure 3.

The primary equations to be used relate directly to the center of mass and its velocity. This will be acquired through the .txt files for the Milky Way and M31 at snapshot 445 that contain the mass and velocity. Rather than using one single equation, using a function to iterate through the data simplifies the calculations. For ease of calculations, the radial distance from the merger remnant's center of mass was a range of values between 0 and 150 kpc. This distance was chosen as it ensured that the mass profiles had reached their total volume.

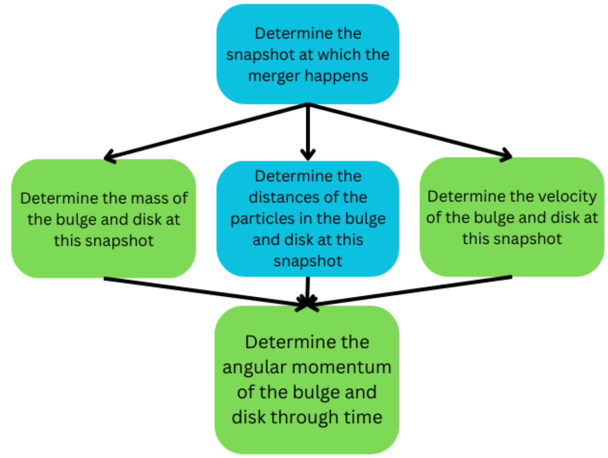

Figure 3. Flow Chart showing anticipated stages of this research. The green shows the data that will be plotted while the blue shows the data that will be used within the plots, but not explicitly plotted itself.

This distance is plotted against total contained mass to determine the mass profile and the velocity to determine velocity dispersion. We can then calculate angular momentum using the equation

$$L = \frac{1}{2}mvr^2$$

where m is the mass, v is the circular velocity, and r is the radius at this point. This equation, in combination with the mass profile and velocity dispersion, allows us to understand the movement, rotation, and evolution of the merger remnant. The most important component, though, will be found through plotting these values against each other. This simply involves running the codes at the determined snapshots and values to plot various profiles. These profiles will further tell us and confirm what parts are rotating and how the mass is dispersed.

These plots in specific refer to those that can be used to determine the mass as a function of radius and the velocity as a function of radius. From these, we can determine if there are mass concentrations in the galaxy, or if it is elliptical and has a relatively consistent mass. The velocity plot would show if one part is rotating faster than another, as can be the case in spirals, or if it is decreasing, such as in elliptical galaxies. For angular momentum, we can plot it against the distance from the center of mass to determine if there is evidence of rotation farther from the center, and possibly even if it is conserved. Overall, these plots can further confirm our findings about the shape of the galaxy and confirm the hypotheses mentioned in the following section. A summary of this outline can be seen in Figure 3

Based on the preceding information, my hypothesis is that we will find a merger remnant that has an elliptical shape. This implies that the angular momentum is not significantly increasing as distance from the center of mass increases, and there will be consistent or less velocity measured since elliptical galaxies do not rotate as much as spiral galaxies do. I believe this is the likely scenario considering previous work done that shows a merger is imminent, and information from these papers and from what we have learned and done in classes to explain galactic mergers shows that an elliptical galaxy is often the resulting shape from galaxy mergers.

4. RESULTS

The mass profile of the merger remnant, seen in Figure 4, shows that most of the mass for both the bulge and the disk is contained within 75 kpc from the center of mass. The total mass of the bulge is about a factor of ten smaller than for the disk for both the Milky Way and M31, and M31's bulge and disk contribute much larger masses (about two times more) than the Milky Way's bulge and disk. Additionally, the mass profile line for the bulge smooths out, or reaches its peak, between 30-40 kpc from the center after its initial mass increase within 5 to 10 kpc. The disk, on the other hand, starts increasing mass around 15-25 kpc and doesn't completely smooth out until around 75 kpc. This, then, shows that the entire mass of the bulge starts closer to the center of mass and is completely contained further within than the disk, which starts farther out and extends a farther distance than the bulge.

As for the velocity profiles, there is a clear decrease in circular velocity past 20 kpc for the disk and beyond the center of mass (0 kpc) for the bulge. These profiles can be seen in Figure 5. The spike at the start of the disk plot is likely due to some parts still merging and interacting with the centers of the merger, which would be black holes in this situation. Since we know from the mass profile that most of the disk mass is not contained here, this can be ignored for the most part. The bulge, which starts gaining mass at the center of merger remnant, very rapidly begins decreasing in velocity. At the distance from the center where the bulge mass profile reaches its maximum mass, the velocity has already decreased by 60 percent and slowly decreases beyond that. For the disk, the velocity decreases most rapidly before around 50-75 kpc before the curve eventually starts flattening out to reach a more constant velocity. Essentially, as the distance from the center of the mass increases, the circular velocity decreases.

With the mass, distance, and circular velocity now calculated at this snapshot, the calculation for the angular

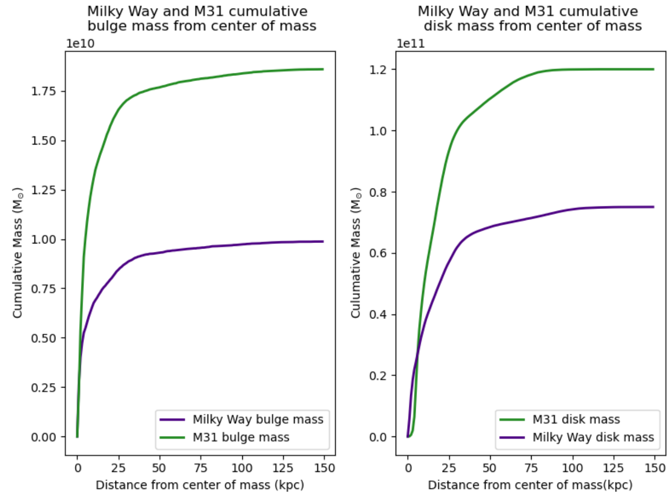

Figure 4. Mass profiles for the bulge and disk of both the Milky Way, in indigo, and M31, in forest green. The masses are calculated in total as a distance (in kpc) away from the center of mass. The bulge reaches its total mass before 50 kpc, while the disk doesn't reaach its total mass until around 75 kpc. The mass for the bulge and disk of M31 is about two times larger than the MW's, and the disk has a factor of ten larger amount of mass than the bulge.

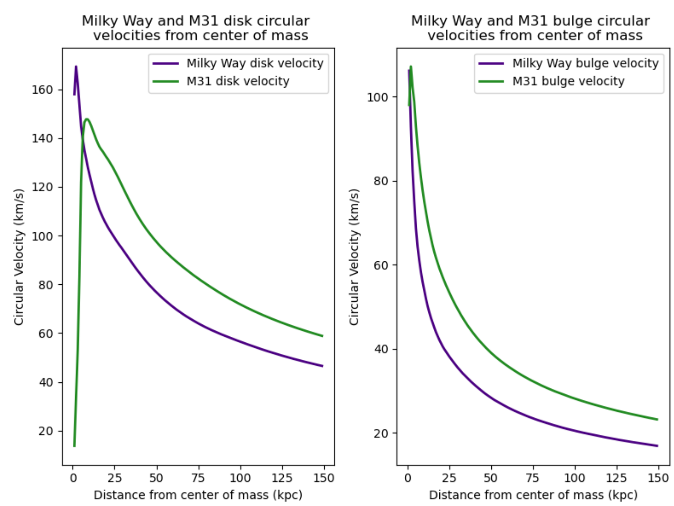

Figure 5. Velocity (km/s) dispersions for both the bulge and disk of the MW, in indigo, and M31, in forest green, plotted against distance from the center of mass (kpc). The velocity decreases for both over time and eventually begins to flatten out to a constant value. The disk's velocity is initially much faster and remains faster as a function of distance from the center of mass. The initial anomaly for the disk is likely due to the fact that parts of the galaxies may still be merging and that the disk does not contain much mass before 15 kpc.

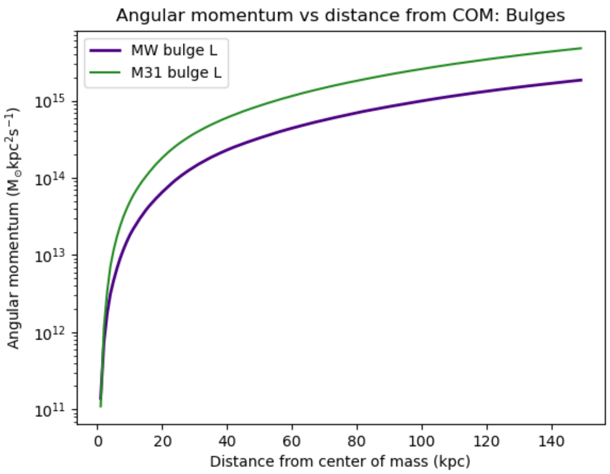

Figure 6. Angular momentum, in kgm^2s^{-1}, as a function of distance from the center of mass in kpc. This was measured for the bulge of the Milky Way (indigo) and M31 (forest green), which increases rapidly until around 40 kpc which is where the mass profile in Figure 4 peaks.

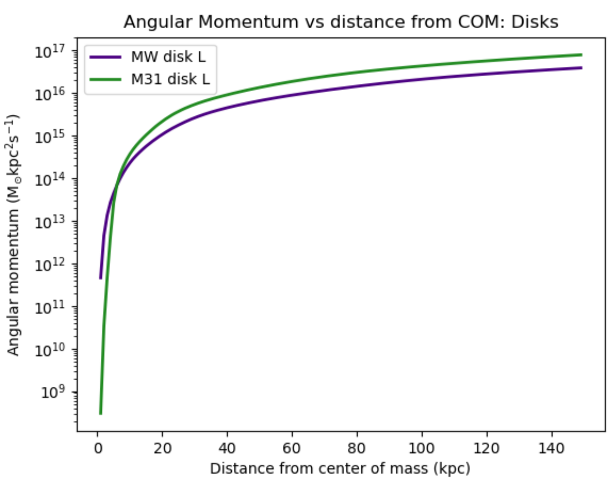

Figure 7. Angular momentum, in kgm^2s^{-1}, as a function of distance from the center of mass in kpc. This was measured for the disk of the Milky Way (indigo) and M31 (forest green), which increases until around 75 kpc which is where the mass profile in Figure 4 peaks.

momentum was done through an iterative function to account for particles at every point, mass, and velocity. For the angular momentum of the bulge, we see in Figure 6 that the angular momentum has begun to smooth out around 50 kpc from the center. The angular momentum flattening out shows that the primary parts of the bulge rotating are nearest to the center of mass. Additionally, the bulge from M31 has a higher magnitude of its angular momentum implying that it contributes more than the Milky Way's bulge.

For the angular momentum of the disk, there is a much higher magnitude than compared to the bulge, by about two factors at the maximum seen in Figure 7. The graph for the disk appears to increase much more rapidly than for the bulge, but this is due to the initial velocity anomaly with the disk. Beyond the initial point, M31's disk dominates over the Milky Way's disk due to its larger mass. Beyond 75 kpc, the angular momentum flattens out and remains mostly constant. Overall, this angular momentum graph shows that the disk is rotating around the center of mass and that the disk is rotating at a similar rate throughout the distance from the center. This supports that the merger remnant is likely elliptical in shape as the disk rotates with a constant increase dependent on distance from the center.

5. DISCUSSION

The mass profiles for both the bulge and the disk of the galaxies align with what would be expected for their distribution. Bulges tend to be concentrated closer in to center of mass, while disks are more dispersed beyond where the bulge ends and for a greater distance than the bulge, too. The disk mass increase can be most clearly seen in M31's increase between 25 and 75 kpc, showing the radius is approximately 50 kpc. The bulge, on the other hand, is seen to increase until around 25 kpc, making the radius approximately 25 kpc. These radii are much larger than these components pre-merger (Cautun et al. (2020)), which is aligned with the expectation for elliptical galaxies. Therefore, the mass profiles support the hypothesis that the merger remnant is an elliptical galaxy.

This mass profile can certainly be confirmed to be of an elliptical galaxy when comparing it to Cautun et al. (2020) and Zhang et al. (2024). In Cautun et al. (2020), the Milky Way mass profile is found to contain essentially its entire baryonic mass, which would be within the disk and bulge, within 10 kpc. Beyond this, the magnitude hardly changes. This is a stark contrast when compared to the merger remnant where the bulge extends to 25 kpc and the disk to 75 kpc. The magnitudes presented for the Milky Way are in line with these measurements, and such is the same for M31, considering that the dark matter mass is not accounted for in our calculations. This confirms that the mass we are measuring is, in fact, conserved and accurate.

There are not many uncertainties that accompany the examination of the mass profile. The magnitudes of the masses, as stated in the previous paragraph, align with measurements of the mass profile before the merger

(Cautun et al. (2020) and Zhang et al. (2024)). Uncertainities may arise from not knowing the exact stopping and starting points from the graph alone as it extends to 150 kpc. This large range makes specific evaluation from images alone difficult, though it still allows for insight into the general trends and behaviors of the galactic mass profile.

The velocity dispersion shows a circular velocity that decreases as a function of distance from the center of mass. The bulge's velocity peaks immediately above 100 km/s and rapidly decreases until 25 kpc, then begins smoothing out. The disk, outside of the initial anomaly, begins its velocity after approximately 15 kpc at around 140 km/s for both disks. After the initial peak, the circular velocity steadily decreases, though not as rapidly as for the bulge. This is likely due to the fact that the disk has a larger radius than the bulge and is more massive. For both the disk and the bulge, M31 is seen to contribute more to the total velocity as it has higher measured values at every point. The merger remnant's velocity dispersion matches predictions based on my hypothesis as the velocity decreases and eventually flattens out as distance from the center of mass decreases.

The velocity dispersion matches the predictions in existing literature as elliptical galaxies are typically slow rotators, indicating a decrease in circular velocity (Cox & Loeb (2008)). For the Milky Way pre-merger, Cautun et al. (2020) shows that the baryonic matter's circular velocity peaks around 160 km/s and steadily decreases through 100 kpc. This baryonic matter would be contained in the bulge and disk, which similarly have peaks around 160 km/s and decrease through 100 kpc post merger. This is important as it shows the qualities of the galaxies pre-merger are preserved after the merger, though the combined characteristics allow these velocities to extend for further distances and higher values overall. M31 having a greater overall mass for both the disk and the bulge, as seen in figure 4, are clearly shown through M31 having higher velocity values throughout the dispersion.

Uncertainties in this analysis may arise from two places: the initial anomaly in the first few kpc and from the range of analysis. The initial anomaly, where M31's disk is measured to begin at 0 km/s which the Milky Way's begins at 160 km/s, likely reflects the interaction between the black holes merging and the baryonic matter as the merger is completed. The range of radii that were analyzed may allow for uncertainties to arise as visual inspection and interpretation of the graph is difficult over large ranges. Having a range through 150 kpc shows how the various components behave over the entirety of the merger remnant. Close-up examination may be more difficult from the plots seen in this work, though the general behavior and trends of these components can be analyzed.

The angular momentum plots, seen in figure 6 and figure 7, show a large increase in angular momentum at the primary points where the bulges and disks gain much of their mass. The disk, appropriately, has a higher magnitude than for the bulge due to its higher mass and higher velocity values. This result agrees with my hypothesis that the angular momentum does not significantly increase as a function of distance from the center of mass. The graphs being concave down shows a decrease in the slope intensity, meaning it is at is highest increasing angular momentum at the curve around 15 kpc for the bulge and 30 kpc for the disk. The disk, in general, has a very large increase in angular momentum through as many as three magnitudes due to the aforementioned large mass and velocity. M31 is also dominant over the Milky Way for both the bulge and disk as was the case for the mass profiles and velocity dispersions. Finally, the angular momentum shows that these components are rotating around the center of mass and the rotation depends on the distance from the center, and the consistent slight increase shows that this merger remnant is an elliptical galaxy.

When the angular momentum of the merger remnant is compared to the Milky Way's angular momentum today, it is clear that our result is an elliptical galaxy. Previous measurements found a gap in the angular momentum that would correspond to the spiral arms of the galaxy (Semczuk et al. (2022)) around 13 kpc. However, this gap is not seen in either Figure 6 or Figure 7, likely due to the remnant not having spiral arms for which gaps can exist. This result is important to understand how spiral galaxies lose their structure as they merge and have a constant angular momentum increase instead as there is baryonic matter consistently through the disk. In fact, there are no gaps seen in the mass profile or velocity dispersion either, proving that the merger remnant is in fact elliptical in shape.

Uncertainties in the angular momentum calculation come from the time at which the merger remnant is analyzed. Snapshot 445 was chosen at it is the initial point where the merger has occurred, meaning the angular momentum is calculated for the earliest point of combination before the remnant may have had time to fully settle into its new dynamics. Part of the angular momentum may still be under the affect of the merger dynamics. For the most accurate angular momentum post-merger, the best snapshot to look at may be 800. This may also ensure that the remnant may be more disk-shaped to match the angular momentum approximation better, though this uncertainty is likely to be low as any point past the initial merger should be similar enough that the exact point does not explicitly matter.

REFERENCES

Cautun, M., Benítez-Llambay, A., Deason, A. J., et al. 2020, Monthly Notices of the Royal Astronomical Society, 494, 4291, doi: 10.1093/mnras/staa1017

Cox, T. J., & Loeb, A. 2008, Monthly Notices of the Royal Astronomical Society, 386, 461–474, doi: 10.1111/j.1365-2966.2008.13048.x

Hopkins, P. F., Hernquist, L., Cox, T. J., & Kereš, D. 2008, ApJS, 175, 356, doi: 10.1086/524362

Lotz, J. M., Jonsson, P., Cox, T. J., & Primack, J. R. 2010, Monthly Notices of the Royal Astronomical Society, 404, 575, doi: 10.1111/j.1365-2966.2010.16268.x

Matteucci, F. 2003, Astrophysics and Space Science, 284, 539–548, doi: 10.1023/a:1024089402368

Semczuk, M., Dehnen, W., Schönrich, R., & Athanassoula, E. 2022, Monthly Notices of the Royal Astronomical Society, 519, 902, doi: 10.1093/mnras/stac3528

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

Zhang, X., Chen, B., Chen, P., Sun, J., & Tian, Z. 2024, Monthly Notices of the Royal Astronomical Society, 528, 2653, doi: 10.1093/mnras/stae025