The Motion of the Dark Matter Halo Remnant of the MW-M31 Merger: Prograde or Retrograde?

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1 INTRODUCTION

1.0.0.1 Galaxies and dark matter halos evolve together through large-scale mergers, with the dark matter halo and the baryonic matter merging on different timescales. **Cold Dark Matter Theory** is the theory that dark matter consists of weakly interacting massive particles (WIMPs) with relatively small thermal velocities, allowing them to form small structures of less than one solar mass (Diemand & Moore 2011). It is now theorized that CDM combines to create a cosmic web structure, connecting everything in the observable universe. In addition to the cosmic web, we can define **Dark Matter (DM) Halos** as a spherical region of higher-density dark matter that surrounds a galaxy (Drakos et al. 2019). DM halos cannot be physically observed using any electromagnetic radiation, but we can observe the gravitational effects on satellite bodies, since the halos extend past the visible baryonic matter of a galaxy, such as the disk. The **stellar disk** is a relatively thin and flat component of a galaxy that contains the majority of a galaxy's stars and stellar material (baryonic material). We can analyze both the DM halo and the stellar disk using their respective important radii. For the baryon disk, the **virial radius** is the radius where the average density of the galaxy inside that radius is approximately 200 times higher than the critical density of the universe (Salucci et al. 2007). For the DM halo, the **Hernquist profile** describes the density distribution of the DM within the halo and produces the scale radius, which represents the radius at which the DM halo goes from high density to lower density (Hernquist 1990; Dubinski et al. 1999). Then we can roughly define where the density of the stellar disk and the DM halo decrease significantly and how certain properties, such as angular momentum, change at different radii throughout a major merger. Because of their size and the large amount of mass that results in stronger gravitational attraction, the DM halos will be the first to interact in a major merger, as well as be the first to interact with other satellite bodies. Therefore, mergers, both minor and major, greatly affect the structure and shape of DM halos (Drakos et al. 2019).

1.0.0.2 Galaxy mergers play a crucial role in galaxy evolution. While galaxies will evolve on their own, mergers allow for a large amount of interaction between two massive astronomical objects. The term **galaxy** is derived from the Greek word for "milky". **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), although Willman & Strader (2012) does discuss other ways to identify and classify galaxies, such as stellar kinematics and [Fe/H] spread. This definition implies a dependence on dark matter, without explicitly saying so, as **Cold Dark Matter (CDM) Theory** is not considered a physical law due to the lack of observational evidence. The term **galaxy evolution** refers to the formation of a galaxy and how that galaxy changes over time. Because CDM halos account for the majority of a galaxy's mass, it follows that the merging of the DM halos would greatly influence the nature of the galaxy remnant.

1.0.0.3 From (Drakos et al. 2019) we know from simulation data that the DM halos take a considerable amount of time for their shape to stabilize, see figure 1. From the same figure, we see that the peak circular velocity remains relatively constant, but the radius at which that circular velocity peaks varies throughout the merger (Drakos et al. 2019). Multiple studies have found that the stellar matter that lies within the disk of a galaxy directly influences the shape of the dark matter halo (Prada et al. 2019). In simulations where baryons are present, the DM halo is much more spherical than in simulations where only DM is present (Chua et al. 2019). Although some studies claim that the orientations of dark matter halos would remain relatively constant through mergers, Baptista et al. (2023) claims, through an analysis with the LMC, that a major merger would result in an alteration in the halos' orientation due to the change in angular momentum. Also, instead of DM halos being supported by rotation, Diemand & Moore (2011) claims that DM halos are instead supported by *almost* isotropic velocity dispersions, but further claims that there is approximately the same amount of positive and negative angular momentum material relative to any reference frame (Diemand & Moore 2011). In addition, Diemand & Moore (2011) argues that at radii greater than 10% of the virial radius, the stellar disk orientation and the DM halo shape are uncorrelated.

1.0.0.4 There are many open questions concerning the evolution of galaxies and dark matter halos through mergers, and these questions are actively being studied. A first major question is how the angular momentum of the DM halo evolves throughout a major merger and if the effects remain after a considerable timescale. Further, it is still in question whether or not the spin of the DM halo remnant favors one galaxy over the other (Rodriguez-Gomez et al. 2017). A second major question outlined in Drakos et al. (2019) is how we can compare a galaxy's substructure to relate its past merger history to its final state. Drakos et al. (2019) discusses many broad conclusions for size, shape, and spin, but notes that more research would be beneficial for clarification. A third major question considering mergers is how the overall mass of the galaxy remnant compares to the mass of each of the host galaxies, due to the fact that large amounts of matter, both

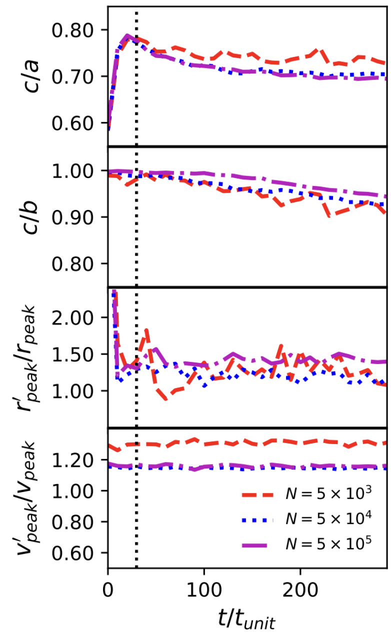


Figure 1. This figure assumes a triaxial halo where a, b, and c represent the major, median, and minor axes, respectively. From the top plot to the bottom plot, the figure analyzes the axis ratios c/a and c/b, as well as the parameters $r'_{\rm peak}$ and $v'_{\rm peak}$ with respect to their original, pre-merger values of $r_{\rm peak}$ (radius at which the circular velocity peaks) and $v_{\rm peak}$ (the peak circular velocity), respectively. All of these variables are plotted with respect to time, and each N represents a different simulation resolution. The vertical dotted lines show the time by which the two DM halos had completely merged. Although the peak circular velocity remains relatively constant, the other parameters take time to stabilize (Drakos et al. 2019).

dark matter and stellar, will be ejected during the merger. Researchers are trying to solve these open questions by using simulation data of various galaxies with various density profiles. Some simulations isolate the DM halo, and some use data for both a stellar disk *and* a DM halo.

2 THIS PROJECT

2.0.0.1 In this paper, we will study whether the DM halo remnant of the Milky Way (MW) and Andromeda (M31) merger will be prograde or retrograde with respect to the rotation of the stellar disk. Prograde motion refers to motion that exists in the *same* direction as the object it is surrounding, whereas retrograde motion refers to motion that exists in the *opposite* direction as the object it is surrounding. In the case of this paper, I will be analyzing the angular momentum of both the DM halo and the stellar disk of both MW and M31 pre-merger and the MW-M31 remnant post-merger. We can compare the direction of the angular momenta in three-dimensional space and determine if there is prograde or retrograde motion occurring. By examining the angular momentum across different times, we can analyze how the motion changes through the MW-M31 merger.

2.0.0.2 Of the open questions previously discussed, this project addresses the first major question about how the angular momentum of the DM halo evolves throughout a major merger. For determining if the DM halo's motion is prograde or retrograde, it is essential that we analyze the angular momentum of both the stellar disk and the DM halo.

2.0.0.3 This question is important for galaxy evolution because DM halos contain a large amount of a galaxy's total mass, even though it is not able to be directly studied using electromagnetic radiation. Because mergers are not an astronomical event that happens on a regular basis within an observable radius, we use simulations of galaxy mergers, both minor and major, to determine the changes that occur throughout a merger. Throughout these mergers, angular momentum can oppose each other as the galaxies collide and cause changes to the stellar disk. A change to the DM halo means a change to the environment that surrounds the other main components of a galaxy (disk and bulge), and so a dramatic change in the halo could result in a change in the baryonic components.

3 METHODOLOGY

3.0.0.1 This project uses simulation data outlined in van der Marel et al. (2012), which discusses the "future dynamical evolution of the system composed of the MW, M31, and M33" (van der Marel et al. 2012) by using N-body simulations and semi-analytic orbit integrations for each of these galaxies. N-body simulation refers to simulations that consider a large number of particles and determine the position and velocity vector of each particle, considering their interactions with each other. This simulation considered only stellar material and dark matter within the local group system (no gas particles). The DM halo was represented using a Hernquist density profile and, for the stellar disk, the virial radius was used to determine many properties such as the virial mass and the concentration (van der Marel et al. 2012).

3.0.0.2 To determine whether the DM halo of the galaxy remnant has prograde or retrograde motion with respect to the stellar disk, we must calculate the angular momentum of both the DM halo and the stellar disk. To do so, we will be using both the stellar disk (type 2) and the DM halo (type 1) particles for the MW and M31 from the simulation data. The resolution is not a crucial part of these calculations, so the low-resolution data will be used. For each particle type, we can calculate the angular momentum and then take the dot product of the disk angular momentum and the halo angular momentum. If the dot product is negative, the orbit of the dark matter halo is prograde. If the dot product is positive, the orbit of the dark matter halo is retrograde. We can plot the sign of the dot product over an array of times (snapshots of the simulation data) to analyze how the rotation of the DM halo evolves throughout the MW-M31 merger. In relation to this plot, one similar to figure 2 could be created to show the difference in the angular momenta of each particle at different radii surrounding the stellar disk. This would require looking at a two-dimensional slice of the three-dimensional simulation data.

3.0.0.3 Firstly, we must rotate the M31 simulation because the data is not represented edge-on as the MW data is. Then, we can calculate the angular momentum of each galaxy component using the following equation for angular momentum, represented as $\vec{L_i}$:

$$\vec{L} = \sum_i \vec{r_i} \times \vec{p_i} = \sum_i m_i(\vec{r_i} \times \vec{v_i})$$

Where the sum is over every particle in the simulation data. m_i, $\vec{r_i}$, and $\vec{v_i}$ represent the mass, position vector (x, y, and z components), and velocity vector (x, y, and z components) of each individual particle. We can import the mass of every particle directly from the simulation data, but the position and velocity vectors need to be adjusted to be in the frame of the center of mass of the galaxy. We can then apply a mask to the position vectors to account for a set amount of either

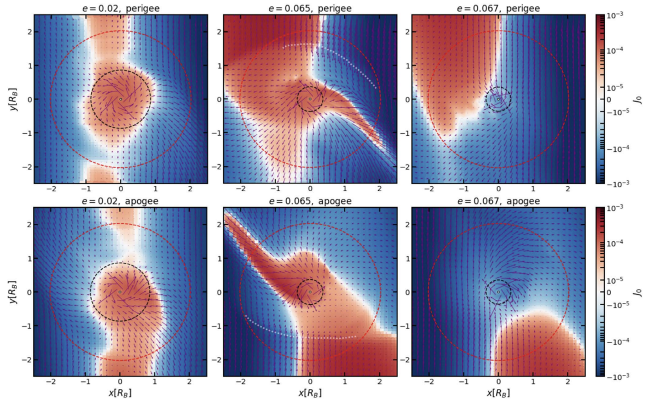


Figure 2. This figure represents the flow pattern of a surrounding body (i.e., DM halo) around an embedded companion (i.e., stellar disk). The color represents the specific angular momentum J_0 relative to the companion. Red represents prograde motion and blue represents retrograde motion. The upper row shows motion at perigee and the lower row shows motion at apogee (Chen et al. 2022).

the stellar disk particles or the DM halo particles so that we are not including particles that are too far away from the merger.

To determine if the dark matter halo is prograde or retrograde, it is necessary to compute the dot product of the angular momenta of the dark matter halo and the baryon disk. For this, we can say the following by definition of the dot product:

$$\vec{L_{halo}} \cdot \vec{L_{disk}} = |\vec{L_{halo}}||\vec{L_{disk}}|cos\theta \rightarrow cos\theta = \frac{\vec{L_{halo}} \cdot \vec{L_{disk}}}{|\vec{L_{halo}}||\vec{L_{disk}}|}$$

The information that will express whether the orbit around the disk is prograde or retrograde is the cosine expression. If the cosine term is negative, the orbit of the dark matter halo is prograde. If the cosine term is positive, the orbit of the dark matter halo is retrograde. We can also analyze how this prograde or retrograde motion changes throughout the merger. To do so, we can choose an array of snapshots to collect simulation data from and perform the above calculations for every snapshot. We can also analyze how the prograde and retrograde motion changes at certain radii. For this, we can choose an array of radii within the scale radius for the DM halo to see how the halo is affected by the stellar disk.

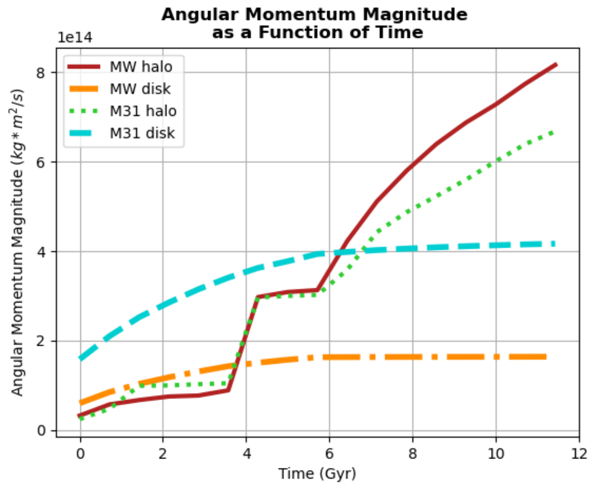
3.0.0.4 The first plot that I will create will be the cosine term from the dot product of the angular momenta versus time. There will be two lines: one representing the MW and the other representing M31. This will demonstrate how the direction of the angular momentum of each galaxy changes with time throughout the merger. The second plot that I create will analyze how the halo motion (the dot product of the angular momenta) varies with radius. This plot will be similar to figure 2 in the sense that it will show how the motion of a surrounding body is prograde or retrograde at certain radii. While it would be ideal to create a plot that is similar in nature to those in (Chen et al. 2022), if we are unable to produce a plot that shows the angular momenta of every particle, it is possible to create a plot with the following design. There will be four lines: one representing the MW pre-merger, another representing M31 pre-merger, another representing the MW-M31 remnant shortly after the merger, and another representing the MW-M31 remnant after the merger when the components are more stable. This plot will demonstrate if the dot product is changing at every chosen radius or if it is relatively constant.

3.0.0.5 After watching video simulations of the local group, it seems that relative to each other, the Milky Way and M31 are rotating in opposite directions. It also seems that the Milky Way has both a prograde and a retrograde component to the dark matter halo rotation, while the dark matter halo of M31 seems to have a prograde orbit (Deason et al. 2011). Because of this, I would hypothesize that the dark matter halo remnant post-collision would orbit retrograde to the baryon disk remnant post-collision. This is due to the fact that as an entire galaxy system, the individual components of each galaxy are rotating in the same direction, but the MW and M31 are rotating in opposite directions with respect to each other. Because the halo has a lower density with the mass more spread out among the halo, I would assume that the disk of the remnant will have more angular momentum than the halo of the remnant because the baryonic matter orbiting within the disk will be moving at greater velocities than the objects within the halo. Considering this, it may be the case that the angular momenta of the disks may affect the angular momenta of the halos throughout the merger. I would also hypothesize that as the radius increases from the galactic center, the direction of the angular momentum would not remain constant shortly after the merger, due to the chaos. I do think that as the remnant has time to stabilize, the prograde or retrograde motion of the DM halo will be constant over the scale radius from the Hernquist profile.

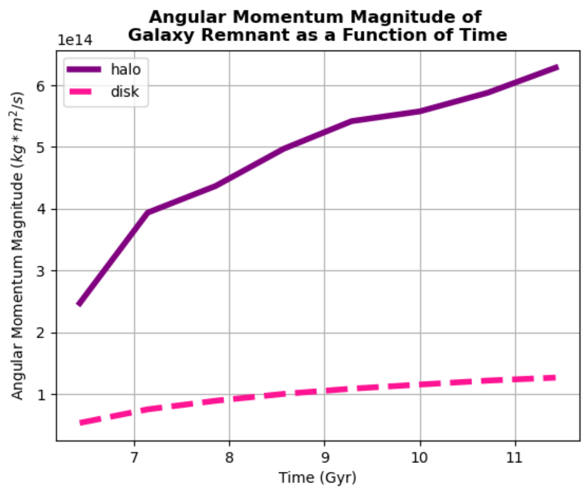
4 RESULTS

4.0.0.1 From figure 3a, we can analyze the magnitude of the angular momentum of the MW and M31 components as a function of time. From the plot, we can see that the magnitude of the angular momentum of both the MW and M31 halo increase throughout time. We see the first major increase during the first close interaction between the MW and M31 which occurs around 4 Gyr. We see the second major increase during the second close interaction between the MW and M31 which occurs around 6 Gyr. We can see that the magnitudes of the angular momenta of the baryon disks increase steadily until stabilizing around 6 Gyr in the future. This is consistent with the idea that the DM halos will have major interactions before the baryonic disks fully interact. We can also see that the disk of M31 has more angular momentum than the disk of the MW but the halo of the MW generally has more angular momentum than the halo of M31. Figure 3b shows a view of the MW-M31 galaxy remnant angular momenta. We can see that the angular momentum of the halo continues to increase as the remnant stabilizes. The angular momentum of the disk also increases but at a much slower rate. We can also see that the angular momentum of the halo remnant is approximately 4 times larger than that of the disk remnant.

4.0.0.2 From figure 4a, we can analyze the motion of the DM halo of each galaxy relative to its baryonic disk. At present day, both the MW and M31 halos have prograde motion relative to their disks. From the present day to the first major interaction at approximately 4 Gyr, the motion of M31 changes between retrograde and prograde multiple times whereas the motion of the MW remains prograde. From figure 4b, we can analyze the motion of the DM halo of the MW-M31 galaxy remnant relative to the disk remnant. Starting at the time of the main merger at approximately 6.42 Gyr, the halo remnant is retrograde to the disk remnant and continues to be retrograde until the end of the simulation data. Therefore, we can conclude that the motion of the MW-M31 DM halo remnant is retrograde relative to the MW-M31 baryonic disk remnant.

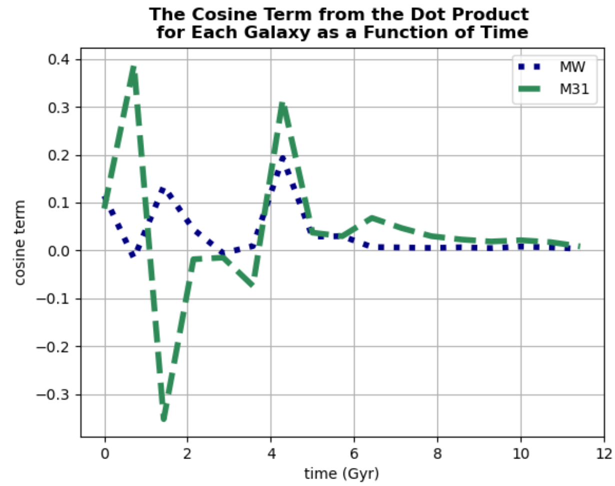


(a) This figure shows the magnitude of the angular momentum of each galaxy component for both the MW and for M31. The y-axis represents the magnitude of the angular momentum of the galaxy component in $kg * m^2/s$. The x-axis represents the time in Gyr from the snapshot data which goes from snapshot 0 to 800 in intervals of 50 so the start time is current-time and the end time is approximately 11.4 Gyr in the future. The solid and dotted lines represent the MW halo and the M31 halo, respectively. The dotted-dashed and dashed lines represent the MW disk and the M31 disk, respectively. This figure shows that the halo angular momenta are generally larger than the disk angular momenta and also increase at a faster rate through time than the disk angular momenta.

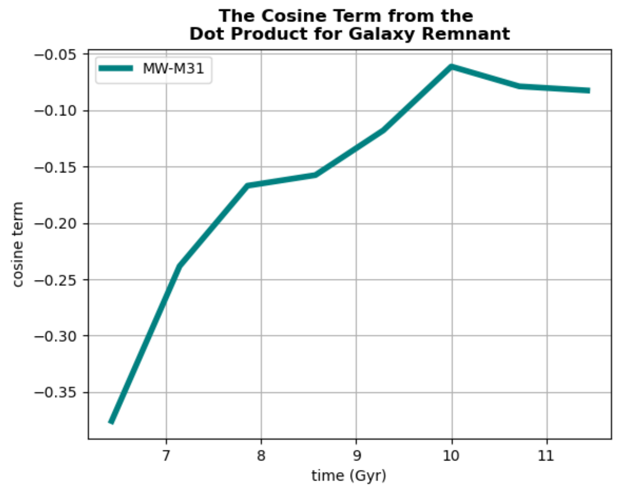


(b) This figure shows the magnitude of the angular momentum of both the DM halo and the baryonic disk of the MW-M31 galaxy remnant. The y-axis represents the magnitude of the angular momentum of the galaxy component in $kg * m^2/s$. The x-axis represents the time in Gyr from the snapshot data which goes from snapshot 450 to 800 in intervals of 50 so the start time is approximately 6.42 Gyr and the end time is approximately 11.4 Gyr in the future. The solid and dashed lines represent the magnitude of the angular momentum of the MW-M31 remnant halo and the MW-M31 remnant disk, respectively. This figure shows that the magnitude of the angular momentum of the MW-M31 galaxy remnant halo increases throughout time at a faster rate than the remnant disk (starting at roughly 3 times larger but ending at roughly 6 times larger).

Figure 3. These figures represent the magnitude of the angular momenta of the MW, M31, and the MW-M31 galaxy remnant as a function of time



(a) This figure shows the cosine term described in the methodology section for both the MW and M31. The y-axis represents the cosine term which can lie between -1 and +1. A negative cosine term corresponds to the prograde motion of the DM halo and a positive cosine term corresponds to the retrograde motion of the DM halo. The x-axis represents the time in Gyr from the snapshot data which goes from snapshot 0 to 800 in intervals of 50 so the start time is approximately 6.42 Gyr and the end time is approximately 11.4 Gyr in the future. The dashed line represents the cosine term of M31 and the dotted line represents the cosine term of the MW. This figure shows that the motion of the MW halo remains prograde while the motion of M31 halo switches between prograde and retrograde two times.



(b) This figure shows the cosine term for the MW-M31 galaxy remnant. The y-axis represents the cosine term which can lie between -1 and +1. A negative cosine term corresponds to the prograde motion of the DM halo and a positive cosine term corresponds to the retrograde motion of the DM halo. The x-axis represents the time in Gyr from the snapshot data which goes from snapshot 450 to 800 in intervals of 50 so the start time is approximately 6.42 Gyr to approximately 11.4 Gyr. This figure shows that starting at the merger time, the halo remnant remains retrograde.

Figure 4. These figures represent the cosine terms for the MW, M31 and the MW-M31 galaxy remnant as a function of time

5 DISCUSSION

5.0.0.1 From figure 4b, we can conclude that the motion of the MW-M31 DM halo remnant is retrograde relative to the motion of the baryonic disk remnant. This is due to the fact that the dot product of the angular momenta of the halo and disk is negative. It is important to note that from figure 4a, the motion of the DM halo of M31 is highly unstable through its interaction with the relatively stable halo of the MW which remains prograde. This does agree with my hypothesis that the dark matter halo remnant post-collision would orbit retrograde to the baryon disk remnant post-collision. This hypothesis was due to the fact that the MW and M31 and their components seemed to be rotating in varying directions which would create enough chaos that the halo remnant and the disk remnant would rotate in opposite directions once the remnant had time to stabilize. Because the motion is determined to be retrograde, it could further be inferred that the angular momenta of the M31 components influenced the remnant's motion more than the components of the MW.

5.0.0.2 We know that DM halos take a considerable amount of time to stabilize (Drakos et al. 2019) and we can see this in figure 4a. In figures 3a and 3b, the angular momenta follows a general trend of increasing throughout the simulation time but in figure 4a, the sign dot product of M31 changes drastically throughout the time pre-merger, which aligns with (Drakos et al. 2019). We also have claimed that major mergers result in an alteration in the DM halo orientation due to the extreme change in angular momenta (Baptista et al. 2023). Again from figure 4a, we can see that throughout the interactions between the MW DM halo and M31 DM halo, the DM halo remnant orientations change significantly as the angular momenta of each component increase as seen in figure 3a. This is meaningful for our understanding of galaxy evolution because this simulation data provides insights into a major galaxy merger between the MW and M31. By calculating the angular momenta of each galaxy's components and analyzing how these values change throughout a major merger, we can determine the nature of the motion of the DM halo remnant and the baryonic disk remnant. We can use these results to predict the behavior of DM halos and baryonic disks of other major mergers and also to make assumptions about the merger history of other galaxies in our observable universe.

5.0.0.3 I have some uncertainties about my plots and how they vary from the total time (figures 3a and 4a) and the time post-merger (figures 3b and 4b). Looking at the total time plots, they seem different from the post-merger plots but I believe that is due to the fact that when plotting the post-merger data, I added the relevant angular momenta as three-dimensional vectors instead of only the magnitudes. If I only added the magnitudes, the plots would be more similar. I also think that for more accurate results, I could use smaller intervals for the snapshots, potentially an interval of 10 snapshots instead of 50. This would allow me to better analyze how the motion of the galaxy components is changing throughout the simulation.

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