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

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ABSTRACT

Galactic mergers take place when two or more galaxies eventually combine to form a galaxy with different overall dynamics. These mergers are a unique and important kind of galactic evolution as they involve how a galaxy interacts and evolves within the context of another galaxy instead of on its own. The most important galactic merger will be the one that involves our own galaxy and Andromeda, also called M31. In order to explore this merger, we must examine how components of the individual galaxies compare and contribute to the merger remnant, which can be done through examining the mass profile of the merger remnant. Examining the mass profile will show what the resulting shape of the remnant is and which components contribute most to the remnant. This research has found that the mass profile shows a merger remnant that is elliptical in shape. This remnant is also dominated by the disk of M31 as it contributes a relatively greater amount of mass. These findings are important to understand how initial galactic mass influences merger remnant dynamics and how components such as disks and bulges evolve and contribute to the merger remnant.

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 galaxies closest 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 galaxies involved. In order to better understand how these dynamics have changed, we must observe how the stellar bulge and the stellar disk will change and contribute to the merger remnant. 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. 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, gas mixtures, and gravity interactions between baryonic and dark matter (Matteucci (2003)). By studying galactic evolution, we can determine many interactions, including which particles or components 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, or even how other galaxies will interact in general. In our case, we are looking at how the remnant of this merger behaves so that we can understand galactic dynamics more thoroughly.

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 on the mass of the galaxies merging (Lotz et al. (2010)), and can depend on the baryonic mass in particular (Lotz et al. (2010)). This is more variable when it comes to smaller galaxy mergers

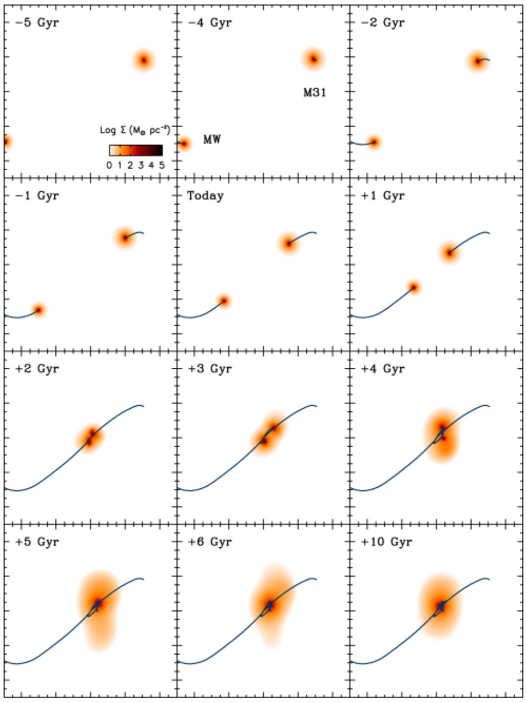

Figure 1. Taken from Cox & Loeb (2008) Projected stellar density throughout the merger of Andromeda (starting in the upper left) and the Milky Way. The time, relative to today, is noted in the upper left corner of each box. It is projected to take approximately 5 Gyr from today to fully merge.

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. The information relating to the mass profiles typically involves the galaxies as they exist right now (Zhang et al. (2024), Cautun et al. (2020)), leaving much to be desired in terms of understanding the mass profile of the merger remnant. Much of our understanding in general comes from how we observe other galaxies merge, visually and dynamically.

Open questions relating to this topic typically involve 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, which is expected to be elliptical (Cox & Loeb (2008)). Besides this, the most relevant open questions pertain to how this merger remnant will be when compared to the galaxies before the merger. Modeling of the mass as a function of distance from the center of mass has been done for both the Milky Way (Cautun et al. (2020)) and M31 (Zhang et al. (2024)), which includes how the circular velocity is changed as a function of distance from this center. The mass profile of the merger remnant and what each component contributes to the total mass have not previously been measured, and thus remains an open question in this subject.

2. THIS PROJECT

In this paper, we will study how the bulge and the disk of both the Milky Way and M31 have evolved after the merger and now contribute fractionally to the total bayronic mass of the remnant. This will be done through measuring the mass as a function of radius from the new center of mass based on particle type. These masses will then be summed together to find the total mass of the baryonic matter in this remnant. Then, the mass of the individual components will be divided by this total mass to determine what fraction of the total mass they contribute. This information will be used to understand their evolution and to confirm the shape of the merger remnant.

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, and the contribution of these elements to the total mass. This work aims to confirm the shape of the remnant to be elliptical, as assumed in Cox & Loeb (2008), and can be used to better understand galaxy mergers throughout the universe, such as the work of Lotz et al. (2010).

Researching this topic is important to understand the mass dispersion of our galaxy and what its evolution is in the context of this merger. Since M31 is much more massive than our own galaxy (Zhang et al. (2024)), it is likely that our galaxy will be heavily influenced and changed through this merger. Analyzing the mass contributions can prove if this will be the case and if previous measurements are correct in assuming the resulting shape will be an elliptical galaxy.

3. METHODOLOGY

The primary coding simulation used calculates the amount of mass contained within a certain distance from a center of mass. This is done by evaluating at a set snapshot number that correlates directly to a point in time, either in the past or future, allowing us examine both the Milky Way and M31 at some point in the merger. To do this, the snapshot number at which the two galaxies have first merged must be found so that we can use the corresponding files containing mass information to create mass profiles. This has been measured to be around 5 Gyr in the future (Cox & Loeb (2008)), which correlates to a snapshot number around 445. These mass profiles will be used to determine the shape of the merger remnant and to determine the fraction of the total mass that each component contributes.

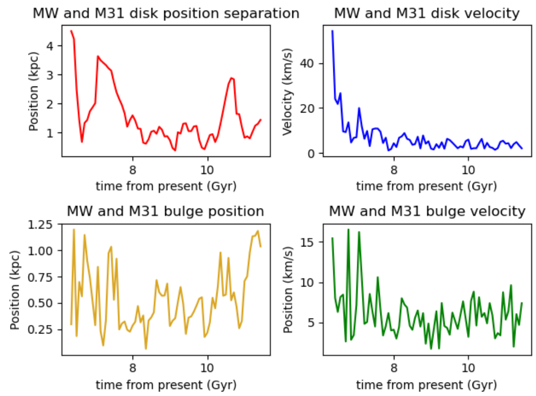

Figure 2. The differences in positions and velocities between the Milky Way and M31 in 5 Gyr and beyond, after they have merged. The separation between the disk and bulge of both of these galaxies is low (<5 kpc) and consistent through time, showing they have merged. Also shown is the difference in velocities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

This starting point ensures that snapshots beyond that represent 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, we can confidently assume that the merger has happened. From here, the mass can be determined at distances from the center of mass that will be given through a standard numpy array. The masses will be taken from the data set according to their particle type: stellar disk (type 2), stellar bulge (type 3), or dark matter halo (type 1) particle, using the Low Resolution files as a more general case is being considered. Then, the total mass of the merger remnant's baryonic matter is calculated for the bulge and disk. An outline of this method can be seen more clearly in Figure 3.

Much of the mass data will be obtained by utilizing iterative functions through coding, rather than explicitly. In the previously mentioned snapshot files, the files are organized by the specific particle mass at specific coordinates. These masses will be used in conjunction with the mass array to determine the total enclosed mass from the center of mass. For ease of calculations, this radial distance was a range of values between 0 and 90 kpc. This distance was chosen as it ensured that the components had reached their total mass. This distance is plotted against total contained mass to determine the mass profile. Finally, these masses will be summed together to be used to determine fractional components.

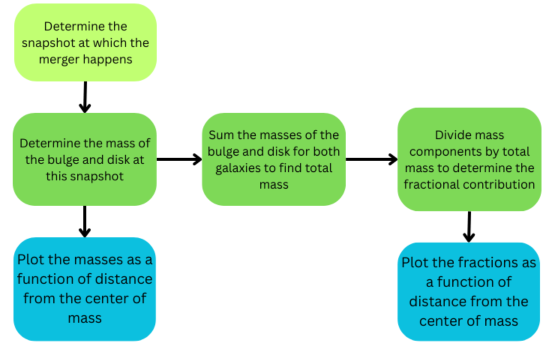

Figure 3. Flow Chart showing anticipated stages of this research. The blue shows the data that will be plotted while the green shows the data that will be used within the plots, but not explicitly plotted itself. The light green shows the information that is being used as the baseline, or what the fundamental information is.

This will be calculated using:

$$f = \frac{M_p}{M_{total}}$$

Here, f stands for the fraction, M_p is the mass of that specific particle type, and M_{total} is the total mass. This will be iterated through to account for the particle mass and total mass at every specific distance from the center of mass.

These mass profile plots refer to those that can be used to determine the total enclosed mass as a function of the distance from the center of mass. Using this plot, one can determine whether there are mass concentrations in the galaxy or whether it is elliptical and has a relatively consistent mass increase. The mass fraction plot that will be created will show which components contribute the most mass, and subsequently controls more of the dynamics of the merger remnant. In general, these plots can further confirm past 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 I will find a merger remnant that has an elliptical shape. This implies that the components extend for larger distances and that the primary component contributing mass is the disk throughout most of the remnant, specifically that of M31. This appears to be the most likely scenario considering that M31 is much larger than the Milky Way (Zhang et al. (2024)) and that the disk is much more massive than the bulge. This hypothesis is also in line with Cox & Loeb (2008) where it was predicted that the merger remnant would be elliptical in shape.

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 60 kpc. The total mass of the bulge is less than 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 20-30 kpc from the center after its initial mass increase within 5 to 10 kpc. The disk, on the other hand, starts increasing mass around 5-15 kpc and doesn't completely smooth out until around 60 kpc. The total cummulative mass, subsequently, increases rapidly until around 25 kpc when it begins to smooth out. 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.

From this information, calculation of what fraction of the total mass each component contributes can be done. This can be seen in Figure 5. Initially, the Milky Way's disk makes up the largest fraction of mass with the bulges of both galaxies contributing the remaining mass. Beyond a few kpc from the center, though, the disk of M31 dominates over not only the Milky Way's disk mass, but the overall fraction of the total mass. Similarly, the bulge of M31 makes up a greater percentage of the total mass than the bulge of the Milky Way. From this plot, it is clear that the disks of the galaxies contribute more to the total mass than the bulges do, and that M31's mass contributes more than the Milky Way's.

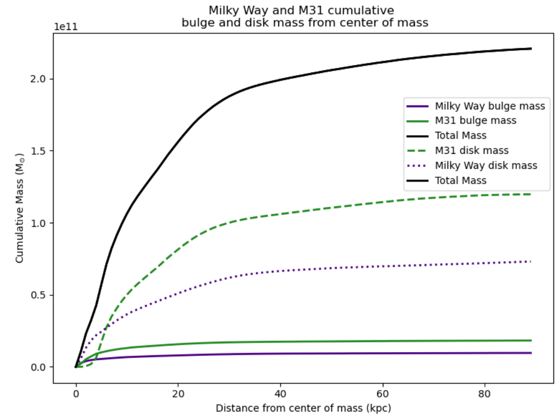

Figure 4. Mass profiles for the bulge and disk of both the Milky Way, in indigo, and M31, in forest green. The masses are calculated in total as a distance (in kpc) away from the center of mass. The bulge reaches its total mass before 50 kpc, while the disk doesn't reaach its total mass until around 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.

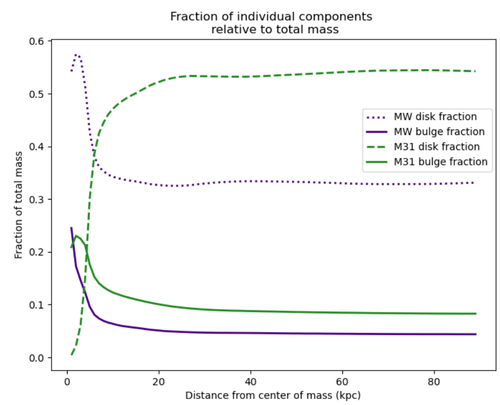

Figure 5. The fraction of the total mass that is contributed by the components of the individual galaxies. The larger initial Milky Way disk mass may be due to outliers in the code that are more apparent as the distance from the center of the mass decreases. The bulge initially contributes a high percentage of the total mass, though at larger distances, the mass of the disk clearly dominates and contributes more to the total mass. In particular, the disk of M31 contributes the highest fraction to the total mass.

5. DISCUSSION

The mass profiles for both the bulge and the disk of the galaxies align with what would be expected for their distribution. The disk's radius is approximately 45 kpc, while the bulge's radius is around 25 kpc. These radii are much larger than these components pre-merger, showing that the evolution from the merger caused these components to extend for further distances, particularly the disk. Since this is aligned with the expectation for elliptical galaxies, 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 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 approximately 20 kpc and the disk to 45 kpc. The magnitudes presented for the Milky Way are in line with these measurements, and such is the same for M31. This confirms that the mass we are measuring is, in fact, conserved and accurate, though extends for larger distances post merger.

There are not many uncertainties that accompany the examination of the mass profile. The magnitudes of the masses, as stated previously, align with measurements of the mass profile before the merger (Cautun et al. (2020) and Zhang et al. (2024)). Uncertainties may arise from not knowing the exact stopping and starting points from the graph alone as it extends to 90 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. Additional uncertainties may come from the calculations beginning at 0, as specific mass calculations at the exact centers of galaxies can be made difficult through the dominance of the black hole.

When looking at how the individual components contribute to the overall total baryonic mass in the merger remnant, it is further evident that the resulting galaxy is elliptical in shape. The disks of both galaxies contribute a very consistent fraction to the total mass, which is over 80% beyond 15 kpc. This disk being massive, dominant, and extensive proves that the resulting merger remnant is an elliptical galaxy. Furthermore, it is apparent that M31's dynamics and mass would dominate the merger remnant as the fractional contribution is consistently larger than the Milky Way's. This is further proved when compared to the results seen in Figure 4 as the components of M31 are certainly more massive than the Milky Way's. These results combined show a resulting galaxy that confirms the hypothesis of an elliptical galaxy remnant.

M31 was previously measured to have a larger mass for the disk and bulge than the Milky Way (Cautun et al. (2020), Zhang et al. (2024)). It is then expected that this galaxy would contribute more to the overall merger remnant than the Milky Way, too, which is what is shown in the resulting plots. The disk making up a majority of the fractional component is in line with how an elliptical galaxy, in theory, should be shaped. Elliptical galaxies have a more consistent baryonic matter distribution unlike spiral galaxies such as the Milky Way and M31 pre-merger. We can see this clearly reflected in the aforementioned mass profiles and through the disk contributing a consistently large fraction of the total bayronic mass.

Given the nature of the calculations, uncertainties are relatively limited outside of those that preexist in the mass profile uncertainties. This would then extend to uncertainties from the large range of analysis and analysis beginning right at 0 kpc from the center of mass. The aforementioned uncertainties with close proximity to the center can be seen immediately in Figure 5 as the Milky Way disk is measured to contribute a very large fraction before rapidly decreasing.

6. CONCLUSIONS

Galactic mergers take place when two or more galaxies eventually combine to form a galaxy with different overall dynamics. These mergers are a unique and important kind of galactic evolution as they involve how a galaxy interacts and evolves within the context of another galaxy instead of on its own. The most important galactic merger will be the one that involves our own galaxy and Andromeda, also called M31. In order to explore this merger, we must examine how components of the individual galaxies compare and contribute to the merger remnant, which can be done through examining the mass profile of the merger remnant. Examining the mass profile will show what the resulting shape of the remnant is and which components contribute most to the remnant.

From the mass profile in Figure 4, it is shown that the mass of the disks is much greater than that of the bulges by an order of magnitude. The bulges also reach their peak mass much earlier than the disks. These results are in line with what would be expected of an elliptical galaxy, proving that the merger remnant is an elliptical galaxy. This is important as it proves that previous measurements and assumptions of the merger remnant are correct, including my own hypothesis.

From the mass fraction in Figure 5, it can be clearly seen that the disk of M31 contributes the most to the total baryonic mass, and that the disks contribute more than the bulges. This result is important as it shows that the dynamics of the merger remnant, which would be primarily influenced by mass, would ultimately be most influenced by the disk's contributions. For galactic evolution, it implies that the disk of the more massive galaxy is important to analyze to understand the merger's evolution overall. This further agrees with my hypothesis as the mass profiles of the galaxies before merging showed that M31 had a greater overall mass, and therefore should contribute more to the remnant.

Future work can expand upon our understanding of the merger remnant by calculating the velocity dispersion to provide further insight into the dynamics of the merger remnant. In particular, a consistent velocity increase would further prove the shape to be elliptical. Further analysis and improvement on the mass profile would likely involve investigating the mass of the dark matter halo. While this mass would likely dominate over that of the disk and the bulge, there would be a greater overview of the dynamics in the merger remnant. It is even possible that some discrepancies at the beginning of the mass profile could be explained through this dark matter mass, though this would require much more extensive research.

7. ACKNOWLEDGEMENTS

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Software citation information aggregated using `The Software Citation Station` (Wagg & Broekgaarden 2024; Wagg et al. 2024).

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