Sérsic profile of the MW-M31 merger remnant

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9 May 2025

ABSTRACT
Sérsic profiles are a mathematical tool used for finding the relationship between the surface brightness and radius of a galaxy. They can be valuable in empirically classifying galaxy morphology as galaxies evolve. I used data from van der Marel et al. (2012); an N-body simulation that explores the MW-M31-M33 system as the MW and M31 merge. That data was used to find the best fit Sérsic profile for the merger remnant. I found that the best-fit profile has a Sérsic index of 3.86, which classifies it as an elliptical galaxy. This result advances understanding in patterns of galaxy evolution and combines the disparate snapshots from observations into a complete story.

Key words: Local Group – Major Merger – Dry Merger – Sérsic Profiles – Elliptical Galaxy – Hierarchical Growth

1 INTRODUCTION

Galaxy morphology, which typically comes from visual description, has a direct relationship to stellar formation history and the history of the galaxy itself. Visual inspection has some level of inherent subjectivity, especially when done by a small number of astronomers. This can be seen in fig:1 where the SDSS images could be easily misclassified. Having specific tools, such as profile fits, gives a quantitative measure to classify these galaxies. For our purposes, a **galaxy** is a collection of gravitationally bound stars, gas, and dust that cannot be described by the properties of that matter and the classical laws of motion (Willman & Strader 2012).

Understanding and classifying galaxies can lead to understanding patterns found in galaxy formation. This understanding can then be used to connect the disparate snapshots, gathered from observations, into a complete picture of galaxy evolution. The formation of elliptical galaxies in particular, is a result of major mergers.

A **major merger** is when the ratio between the two parent galaxies does not exceed 1/3. This type of merger results in dramatic disturbances in the stellar disk/bulge morphology. In general, galaxies will build up over time, through mergers, each associated with morphological changes. These changes will eventually lead to massive, elliptical galaxies (Duc et al. 2012). This process is called **hierarchical growth**. An **elliptical galaxy** is a galaxy that appears to be large, smooth and spheroidal without any other larger defining features (Masters 2012). Typically, elliptical galaxies are a result of dry mergers between spiral galaxies, which removes the structure found in the parent galaxies (Aceves et al. 2006). These final structures are dependent on the precise initial conditions of the parent galaxies (Querejeta et al. 2014). The Milky Way (MW) - Andromeda (M31) major galaxy merger is the system where the most accurate conclusions for the merger remnant can be drawn. The initial conditions of the system are very well constrained because these galaxies lie with the local group, our galactic neighborhood. The **local group** can be more specifically defined as the nearby cluster of gravitationally-bound galaxies that is dominated by MW, M31 and their satellites (van den Bergh 1999). These present-day galaxies can be studied through their surface density (brightness) profiles. This paper uses the **Sérsic Profile**. Which can be defined as:

$$I(r) = I_e \exp(-7.67[\frac{r}{R_e}^{\frac{1}{n}} - 1]) \tag{1}$$

Where I(r) is the intensity as a function of radius, I_e is the intensity at the effective radius, r is the radius in question, R_e is the effective radius (2D radius where half the light is contained), and n is the Sérsic index. This particular version of the Sérsic profile is commonly used for analysis of elliptical galaxies and assumes that the mass to light ratio ($\frac{M}{L}$) is 1. If that is true, then the Sérsic profile is also the mass surface density profile. This profile comes from the $I \propto R^{\frac{1}{n}}$ relationship. Here I is the intensity, R is the radius in question, and n is the index. Classical elliptical galaxies follow de Vaucouleurs profile which has an index of 4. The Sérsic index can be used to analyze how well the merger remnant fits to the expected surface density of an elliptical galaxy. Therefore, providing a quantitative measure for how well the Sérsic profile fits the classical elliptical profile. Sérsic profiles as a whole can be used to analyze a whole host of galaxies using objective profile fits rather than subjective visual classification.

In terms of the classification of galaxies as a whole, there is, in some samples, a correlation between pitch angle and the bulge size. This correlation is missing in other samples, particularly for more massive spirals (Masters 2025). As surveys continue to improve in resolution and depth, more morphologies and patterns within them will be revealed (Masters 2025). For galaxy formation and merger history, the question of how high redshift elliptical galaxies would have formed given the traditional galaxy merger model is not resolved (Duc et al. 2012). Additionally, the level at which accretion history impacts galaxy mass growth is still an open question (Duc et al. 2012). Open questions in the area of major merger morphology include: Can major mergers lead to lenticular (S0) galaxies (Eliche-Moral et al. 2018)? What kinds of galaxies are merging (Hopkins et al. 2008)? At what redshift are these mergers occurring (Hopkins et al. 2008)? How is there still a disk and bulge in an S0 galaxy if it formed from a major merger (Querejeta et al. 2014)? What is the timescale for

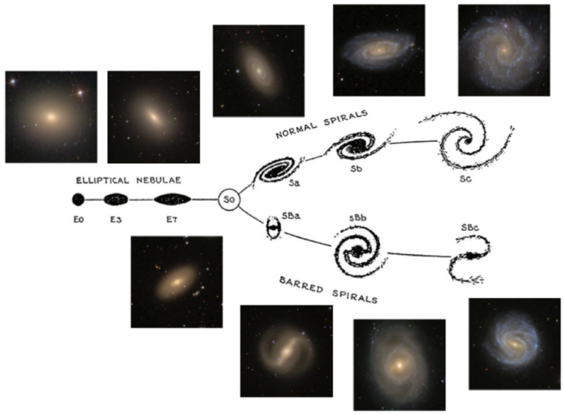

Figure 1. The Hubble tuning fork. This particular version is from Masters (2025) and also includes example galaxy images from the Sloan Digital Sky Survey (SDSS). As a whole this is an overview common morphologies and classifications of galaxies.

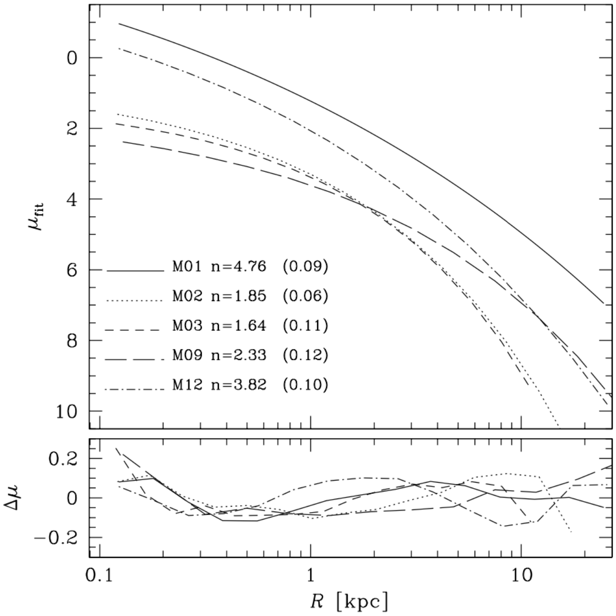

Figure 2. Figure from Aceves et al. (2006). Various Sérsic profiles with various indices. The root mean square of the fit is shown in parentheses. The bottom panel shows the change in surface density. The Sérsic profile is changing rather dramatically with the change in index.

a major merger (Lotz et al. 2008)? How have large-mass elliptical galaxies formed at high redshifts (Duc et al. 2012)?

2 THIS PROJECT

In this paper, I explore the role of dry galaxy mergers between spirals in the formation of elliptical galaxies. This is done by finding the best fit Sérsic profile to analyze how well the MW-M31 merger remnant can be described as a classical elliptical galaxy.

This project is attempting to clarify the morphology of the merger remnant. This is a partial answer to the question of what kinds of galaxies are merging to result in the elliptical galaxies that are observed. It is also a partial answer to how accretion history effects hierarchical growth.

These open questions are directly related to how galaxy mergers affect the resulting elliptical galaxy. Understanding the MW-M31 merger and its remnant will provide a data point for what sort of galaxy results from these major, dry mergers.

3 METHODOLOGY

I will be using data from the N-body simulation found in van der Marel et al. (2012). An **N-body simulation** can be defined as a simulation of a large number of particles that obey the principles of classical dynamics. van der Marel et al. (2012) takes the initial, present day, conditions of the MW, M31 and M33 galaxies and runs the simulation to approximately 10 Gyr into the future. From the limitations of the simulation, a dry merger is assumed. A **dry merger** is one that has a very limited gas supply. This in turn means that the galaxy merger will not lead to star formation. Each galaxy in van der Marel et al. (2012) has a disk with an exponential profile (n=1). MW and M31 have a bulge that follows the de Vaucouleurs profile (n=4), with M33 lacking a bulge. Each galaxy also has a dark matter halo that follows a Hernquist profile.

I used the low resolution (LowRes) files, at snapshot 500. Because I am not interested in the morphology of the dark matter of the remnant, I only pulled the disk and bulge particles. The LowRes files were chosen because I am not interested in the exact location of any particles. Snapshot 500 was chosen because it is comfortably after the MW-M31 merger, which happens at approximately snapshot 445.

I primarily used code created in class to find the Sérsic profile for the merger remnant. This meant adapting the code from lab 6. I use the same assumptions that were made in that code. I only vary the Sérsic index and assume that the mass to light ratio remains constant at 1. Because I pulled disk and bulge particles for both MW and M31, the data needed to be combined and adjusted to all be in the same inertial frame. The Center of Mass code that was previously written was adapted to concatenate the arrays from both of the galaxies and both particle types. The positions are then adjusted to be respect the the center of mass of the system. In order to find the best fit Sérsic profile, which was defined in Equation (1), I tested various Sérsic indices and measured the goodness of fit for each profile using Chi Squared error. Which can be defined as:

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i} \tag{2}$$

where χ^2 is the error, O_i is the observed measurement and E_i is the expected value. In this case O_i is the generated Sérsic profile and E_i is the data from the simulation. The profile with the smallest χ^2 is the best fit to the surface density.

I plotted the best fit Sérsic profile and the de Vaucouleurs profile over the mass surface density as a function of distance for the merger remnant at snapshot 500 and the MW as it appears at the beginning of the simulation. These plots visually show the goodness of fit for the profile with the smallest Chi Squared error. The second plot is a measure of the Chi Squared error as a function of Sérsic index for indices from 0 to 10 in increments of 0.01. I iterate over each of these indices and compare each profile to the data from the simulation to reach an error measurement. This give a visual analysis of how the fit is changing as a function of Sérisc index.

I expect that the final merger will fit quite will as a classical ellip-

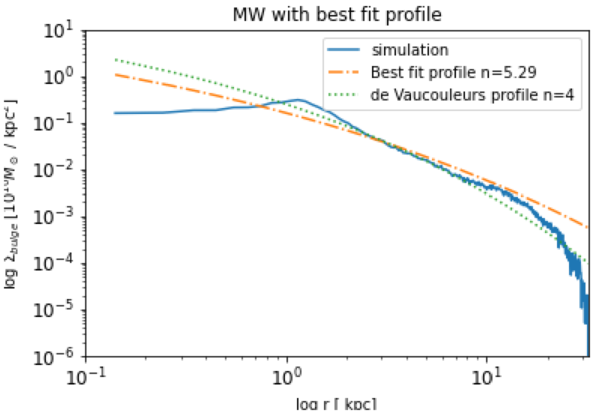

Figure 3. Best fit profile for the initial conditions of the Milky Way disk and bulge particles. This plot is surface density as a function of radius in kpc. The solid blue line is the data from van der Marel et al. (2012). The orange dashed line is the best fit profile and the green dotted line is the de Vaucouleurs profile. The index with best fit is 5.29 which indicates at the disk and bulge do not conform to one particular morphology.

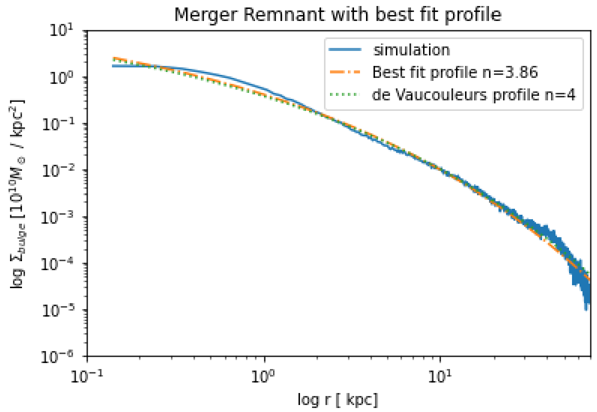

Figure 4. Best fit profile for the merger remnant which shows surface density as a function of radius in kpc. The lines are the same as in fig:3. The best fit Sérsic profile has an index of 3.86 which is sufficiently close to n=4 to prove that the merger remnant is elliptical.

tical galaxy. This is supported by Aceves et al. (2006) who explicitly state that in their simulations elliptical galaxies have come from major spiral mergers. Additional support is given by Hopkins et al. (2008), that found elliptical merger remnants with masses $M_{sph} \geq 10^{11} M_{\odot}$ are overwhelmingly classical elliptical galaxies.

4 RESULTS

The first figure I generated, fig:3, contains the surface mass density as a function of radius, the de Vaucouleurs profile, and the best fit profile for the initial conditions of the MW. This plot is fairly similar to what was generated in lab 6 but the surface density is of both the disk and bulge particles which results two distinct slopes. The best fit profile has an index of 5.29 with an error measurement of 12.08. This means that the MW at the beginning of the simulation cannot be described as an elliptical galaxy.

Fig:4 is very similar to fig:3 however, it uses data for the merger remnant. It combines MW and M31 data for both the disk and bulge particles at snapshot 500, or 7.1 Gyr after the simulation begins. There is only one distinct curve indicating that the particles no longer have disk/bulge distinctions. The best fit profile has an index of 3.86 with and error of 0.94.

The second figure type, fig:5, is a measure of the error between each profile I generated and the simulation data for the merger remnant. This error was measured via Chi Squared. There is a dramatic dip in the error at just below n=4, indicating that the best fit is found at that location.

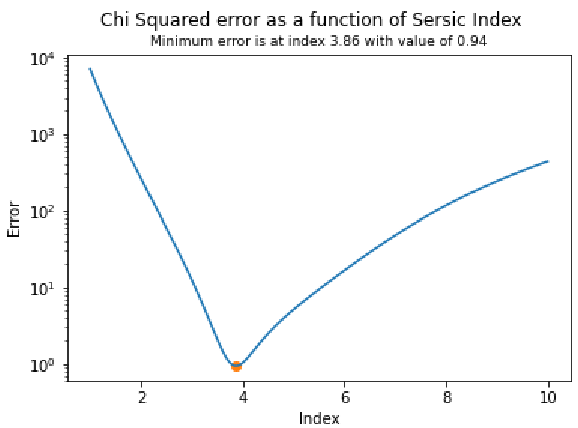

Figure 5. Chi Squared error measurement for the Sérsic profile of the merger remnant tested at various indices. Error measurement is in log space along the y-axis and all of the Sérsic indices that were tested are along the x-axis. The orange dot is the point of minimum error which has a value of 0.94 found at index 3.86.

5 DISCUSSION

The merger remnant can be described as a classical elliptical galaxy; the best fit Sérsic index is shown to be n = 3.86. On a visual inspection of the n = 4 profile, it is incredibly similar to the best fit profile. In fact, the de Vaucouleurs profile only has an error of 1.03. For the initial conditions of the MW, the error was significantly higher with a minimum at 12.08. This is reasonable since the initial MW conditions contain both disk and bulge particles. Both particle types have different properties and could likely be individually fit for discrete indices. The disk and bulge should have quite different profiles. Combining these two particle types with differing properties inherently decreases goodness of fit.

This result supports Aceves et al. (2006) in showing that a disk merger will lead to an elliptical remnant. It also supports the conclusions of Hopkins et al. (2008) that remnants with mass greater than $10^{11} M_{\odot}$ are overwhelming classical elliptical galaxies.

The fact that the best fit profile is n = 3.86 and not exactly n = 4, indicates that there is some amount of uncertainty in my analysis. The limitations come to how I vary the Sérsic profile. I only change the index value while maintaining the assumption that $\frac{M}{L} = 1$. I also only test one snapshot of the simulation after the merger. Expanding upon either of these assumptions will give more accurate conclusions.

6 CONCLUSIONS

Sérsic profiles as a mathematical tools can be used to quantitatively classify galaxy morphology. To explore this topic, I used data from van der Marel et al. (2012); an N-body simulation that explores the MW-M31-M33 system as the MW and M31 merge. That data was used to find the best fit Sérsic profile for the MW-M31 merger remnant.

The MW-M31 merger remnant has a Sérsic index of 3.86 with a Chi Squared error of 0.94 for the fit of the profile. This result supports the hypothesis that the remnant is a classical elliptical galaxy that can nearly be fit by a de Vaucouleurs profile.

An improved analysis could be done by varying more parameters in the Sérsic profiles. This should give a better overall fit. A more sophisticated measure of error perhaps across multiple parameters of the Sérsic profile would also give a better fit. It would be worth exploring how the profile changes throughout the merger and through the rest of the simulation by performing this same kind of analysis on a wider variety of snapshots. This merger morphology could be further investigated with more specific classifications as outlined in Masters (2025).

ACKNOWLEDGMENTS

I would like to thank Himansh Rathore and Dr. Gurtina Besla for providing valuable guidance and input throughout this project.

We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. The University strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

This work made use of the following software packages: `matplotlib` (Hunter 2007), `numpy` (Harris et al. 2020), and `python` (Van Rossum & Drake 2009). Software citation information aggregated using `The Software Citation Station` (Wagg & Broekgaarden 2024; Wagg et al. 2024).

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