Sérsic profile of the MW-M31 merger remnant

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29 April 2025

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

1 INTRODUCTION

The Milky Way - Andromeda (M31) galaxy merger is the system where the most accurate conclusions for the merger remnant can be drawn. This is because those galaxies lie within the **local group** or our galactic neighborhood. Therefore the initial conditions of this system can be well constrained. 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 classical laws of motion (Willman & Strader 2012). The MW-M31 merger can be classified as a **major merger**. This is a merger between two galaxies where the ratio of their size does not exceed 1/3. For the purposes of this project, a dry merger is assumed. A **dry merger** is one that is has a very limited gas supply. This in turn means that the galaxy merger will not lead to star formation. An **elliptical galaxy** is a galaxy that appears to be large, smooth and spheroidal (Masters 2012).

Understanding and classifying galaxies can lead to understanding patterns in galaxy formation. This understanding can 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 which are difficult to explore how exactly they evolve.

Major galaxy mergers cause 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. Specifically, dry mergers between spirals result in elliptical galaxies with highly altered structure from 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). These present-day galaxies can be studied through their surface density (brightness) profiles. For elliptical galaxies in particular, the **Sérsic profile** is used. Which can be defined as:

$$I(r) = I_0 \exp(-7.67[\frac{r}{R_e}^{\frac{1}{n}} - 1]) \quad (1)$$

Where I(r) is the intensity, I_0 is the central intensity, 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 assumes that the mass to light ratio ($\frac{M}{L}$)is 1. If $\frac{M}{L} = 1$ 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 and R is the radius in question. The de Vaucouleurs profile, which is typical for elliptical galaxies, uses n = 4. The Sérsic index can be used to analyze how well the merger remnant fits to the expected surface density of an elliptical galaxy. Sérsic profiles as a whole can be used to analyze a whole host of galaxies using objective profile fits rather than subjective visual classification.

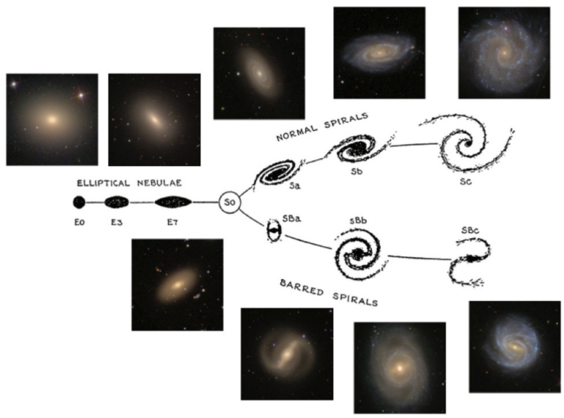

Figure 1. The Hubble tuning fork. This particular version is from Masters (2025) and also includes example galaxy images from the Sloan Digital Sky Survey. As a whole this is an overview common morphologies and classifications of galaxies.

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

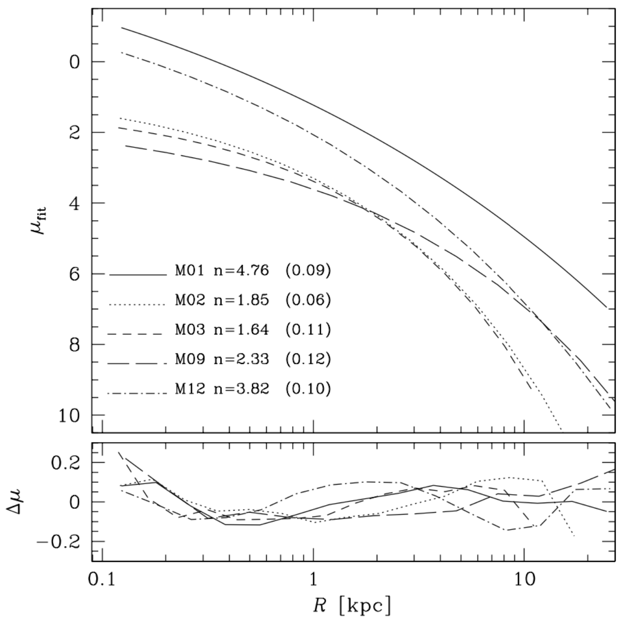

Figure 2. Figure from Aceves et al. (2006). Various Sérsic profiles with various indices. The root mean square of the fit is shown in parentheses. The bottom panel shows the change in surface density. The Sérsic profile is changing rather dramatically with the change in index.

2 THIS PROJECT

In this paper, we will explore the role of dry galaxy mergers between spirals in the formation of elliptical galaxies. This will be 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 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 effect the resulting elliptical galaxy. Understanding the MW-M31 merger and its remnant will provide a data point for what sort of galaxy is the result of 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 and runs the simulation to approximately 10 Gyr into the future.

The code uses the low resolution files (LowRes), at snapshot 500. Because I am not interested in the morphology of the dark matter of the remnant, I pull the disk and bulge particles. The LowRes files were chosen because I am not interested in the exact location of particles. Snapshot 500 is comfortably after the Mw-M31 merger which happens at approximately snapshot 470.

I primarily used code created in class to find the Sérsic profile for the merged 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 is 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 frame. This involves concatenating arrays and finding the center of mass of the entire system. To do that, the Center of Mass code we have previously written was adapted. In order to find the best fit Sérsic profile, which was defined in Equation (1), I test various Sérsic indices and measure the goodness of fit for each profile using Chi Squared error. Which can be defined as:

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

The profile with the smallest χ^2 is the best fit to the surface density of the merger remnant.

I plot the best fit Sérsic profile over the mass surface density as a function of distance for the merger remnant. This plot will 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. This is a measure of the how the fit changes with Sérsic index.

I expect that the final merger will fit quite will as a classical elliptical galaxy. This is supported by Aceves et al. (2006) who explicitly state that their simulations of disk galaxy mergers have led to Sérsic indices that match the observed indices for early type galaxies. Additional support is given by Hopkins et al. (2008) that found spheroidal merger remnants with masses $M_{sph} \geq 10^{11} M_\odot$ are overwhelmingly classical elliptical galaxies.

4 RESULTS

The first figure I generated is a contains the surface density as a function of radius, the de Vaucouleurs profile, and best fit profile for the merger remnant. This plot is fairly similar to what was shown in lab 6 but contains the disk and bulge particles from both the MW and M31. The best fit profile was found to have a Sérsic index of 3.86 which is sufficiently close of the de Vaucouleurs profile of n=4.

The second figure is a measure of the error between each profile I generated and the simulation data. This error was measured via Chi Squared. For the merger remnant, the minimum error is 0.94. For the initial MW, the error was somewhat higher with a minimum error of 12.08. This is reasonable since in MW contains both disk and bulge particles. For the disk an index of 2 is expected and an index of 4 is expected for the bulge. Combining these two particle types with differing properties inherently introduces error. The Chi Squared error is minimized for the Sérsic index that best fits the surface density of the galaxies in the simulation

5 DISCUSSION

The best fit Sérsic index for the merger remnant is shown to be n= 3.86. This result support my hypothesis that the remnant will be a classical elliptical galaxy.

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) where remnants with mass greater than $10^{11} M_\odot$ are overwhelming classical elliptical galaxies. This merger morphology could be further investigated with more specific classifications as outlined in Masters (2025).

The limitations of this analysis come down to how I vary the Sérsic profile. I only change the index value while maintaining the assumption that the mass to light ratio is 1. I also assume a relationship between the scale hight and effective radius. These assumptions

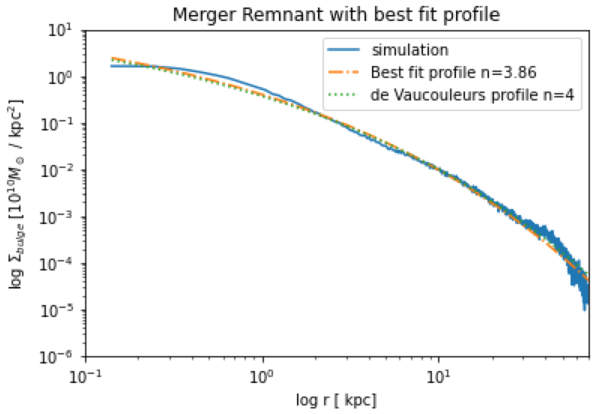

Figure 3. Best fit profile for the merger remnant which shows surface density as a function of radius in kpc. The solid blue line is the data from (van der Marel et al. 2012). The orange dashed line is the best fit profile and the green dotted line is the de Vaucouleurs profile. The best fit Sérsic profile has an index of 3.86 which is sufficiently close to n=4 to prove that the merger remnant is elliptical.

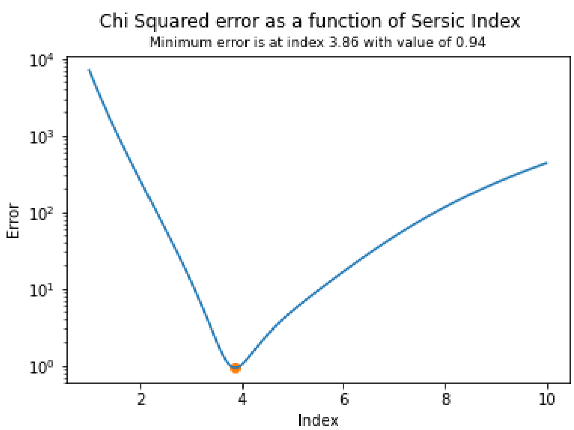

Figure 4. Error measurement for the Sérsic profile tested at various indices. Error measurement is in log space along the y-axis and all of the Sérsic indices that were tested along the x-axis. The orange dot is the point of minimum error a value of 0.94 found at index 3.86.

inherently introduce uncertainty into my calculations, this could be eliminated by performing more elaborate variations to my profile calculations.

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