Disk and Bulge Luminosity Profile Evolution During the MW-M31 Major Merger

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1. INTRODUCTION

1.1. *Proposal*

I will examine the evolution of the luminosity profiles of the Milky Way (MW) and Andromeda (M31) galaxies throughout the course of their simulated future merger. This includes the bulge and disk only, with M33 and dark matter particles not being considered for this analysis. The simulated merger is constructed from a collisionless N-body simulation as described in van der Marel et al. (2012a), where the present-epoch center of mass (COM) velocity for M31 has radial and tangential components of $V_{\rm rad} \approx -109$ km s^{-1} and $V_{\rm tan} \approx 17$ km s^{-1} with respect to the MW (van der Marel et al. 2012b). With this simulation and others, van der Marel et al. found an expected merger of the MW and M31 in ∼6 Gyr after a first pericenter in ∼4 Gyr. Luminosity profiles will be fit in terms of Sérsic profiles (Sérsic 1963; Sérsic 1968) at different time snapshots throughout the course of the merger. See Figures 1 and 2 for examples of what a luminosity profile plot at a *single snapshot* may resemble. In Figure 2, Sérsic profiles were fit explicitly, and in Figure 1 the surface mass density Σ was plotted against $R^{1/4}$ so as to show a straight line indicating a de Vaucouleurs profile (de Vaucouleurs 1948). A de Vaucouleurs profile can be described with a Sérsic index $n = 4$, indicative of an elliptical galaxy or classical bulge. Assuming a particular mass-to-light ratio allows for the conversion $\Sigma \to I$.

1.2. *Motivation*

Major mergers, including the future meeting of the MW and M31, are the most transformative events that galaxies may undergo after their formation. However, many of the details of these mergers are still ill understood. While we can directly observe some galaxy mergers in progress, e.g. NGC 4678 A&B (The Mice Galaxies), we cannot measure the proper motions of these merging galaxies. The MW-M31 system is unique in that we can directly measure the proper motions of stars in each galaxy (Sohn et al. 2012), leading to measurements of the velocities of the COM of the MW and M31 (van der Marel et al. 2012b). This permits the construction of a more accurate model of the current and future dynamics of the stellar components of the largest members of the Local Group (van der Marel et al. 2012a).

At the beginning of the simulation, we have two large spiral galaxies ($M \approx 10^{12}$). M31 has a large classical bulge (Kormendy et al. 2010), while the MW has a smaller pseudobulge. Pseudobulges are not spherically symmetric, are rotation-supported, and have Sérsic indices $n \leq 2$ (Brooks & Christensen 2016). In this simulation, however, the MW is modeled with a classical bulge more similar to that of M31. By the end of the simulation, we have a single merger remnant which is well described by this de Vaucouleurs, $n = 4$ surface density profile, making it most similar to field elliptical galaxies (van der Marel et al. 2012a). For this project I am interested in what is happening to the MW and M31 in the middle, during their metamorphoses from disks with bulges to an elliptical galaxy. Understanding how spiral galaxies may evolve to form ellipticals through majors mergers can help inform our understanding of elliptical galaxy formation, beyond our wanting to understand the fate of our own MW galaxy and the Local Group as a whole.

1.3. *Contemporary Understanding*

It is understood that the merger of the MW and M31 will mostly likely cause the two spiral galaxies to ultimately coalesce into a single elliptical galaxy. Collisionless interactions between the stars of the MW and M31 lead to largely random orbits, in line with field elliptical galaxies and juxtaposed with the ordered rotation of the present MW and M31 spirals (van der Marel et al. 2012a). The evolution of the bulge and disk *throughout* the merger were not explored in detail by van der Marel et al., where the final state of the merged remnant was a larger focus of the analysis. Galaxy mergers have been examined as possible creators of elliptical galaxies for a long time (Toomre 1977), but there are still concerns that mergers by themselves may be not be able to reproduce all relations observed for elliptical galaxies (Brooks & Christensen 2016).

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By studying the process by which the MW and M31 come to form an elliptical galaxy, we may be able to better understand when and how ellipticals are formed through major mergers. Additionally, it is believed that mergers (including minor mergers) could be the source of classical bulges (Brooks & Christensen 2016). Finally, major mergers are thought to be a way to transform spiral galaxies into S0 galaxies, as an alternative to their being viewed as "faded spirals" which cannot explain all the observed properties of S0s (Querejeta et al. 2015b). Major mergers often destroy the original bulge and disk structures of the merging galaxies, but but it is possible that these are rebuilt to create S0 galaxies (Querejeta et al. 2015a). Examining major mergers of spiral galaxies is important then to understanding the formation of elliptical galaxies, S0 galaxies, and classical bulges in spiral galaxies.

1.4. *Open Questions*

This simulated merger has implications for our understanding of field elliptical galaxies, and there are many open questions concerning galaxy evolution and major mergers: did some field elliptical galaxies form from major mergers like that of the future MW-M31 merger? If so, could *all* of them have formed this way? Are some or all classical bulges formed from galaxy mergers? Are some or all S0 galaxies formed by major mergers? Further examination of simulated major mergers will help to bring us closer to answering some or all of these questions.

2. PROPOSAL

2.1. *Questions to Address*

I will address the evolution of the luminosity profiles of the bulge and disk components of the MW and M31 throughout the merger, by fitting to Sérsic Profiles where Sérsic indices n are allowed to vary. Of particular interest will be the question of how these Sérsic indices change throughout the simulated merger, and *when* they change the most. We may expect the greatest changes to be at pericenters or just after pericenters. An increase in Sérsic index indicates that more stars are being concentrated in the center of a galaxy. These higher concentrations in galactic centers yielding $n > 2$ are indicative of elliptical galaxies and classical bulges, where lower Sérsic indices ($n \sim 1$) better describe spiral galaxies with more of their light distributed further out in disks. Changes in Sérsic indices for the bulges and disks of the MW and M31 throughout the simulated merger will help describe how two spiral galaxies can come to form an elliptical galaxy.

2.2. *Proposed Methods*

Sérsic profiles will be fit similarly to the method of Lab 6, but will be made more robust by using `scipy.optimize.curvefit()`, potentially only fitting profiles to beyond a cut-off radius so as to neglect the innermost components that do not follow well Sérsic profiles. Sérsic profiles as a function of radius r are given by the equation,

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

where $L = 7.2 I_e \pi R_e^2$ for the galaxy, and I_e and R_e are the equivalent (half-light) intensity and radius, respectively. I_e and R_e can be calculated at each snapshot from the surface brightness profile, and n can then be varied to best fit the simulated data. When only considering simulated stellar particles, we can take $M_{\rm stellar}/L = 1$ to get a surface brightness profile from a surface mass density profile.

This will be attempted at *all* snapshots using for loops through snapshot data files, but if that proves too difficult then snapshots of particular interest will be selected to best show the evolution. All programming and plotting will be done in Python with the `Matplotlib`, `Numpy`, and `SciPy` modules. Refer again to Figures 1 and 2 for examples of what my plots at a single snapshot may resemble. If I have time, I may also create animations of these Sérsic profile–fit plots as the simulation progresses. This would allow for the changes in the luminosity profile and Sérsic indices to be more easily seen, or otherwise I may create a plot of n versus t. An animation could be created by importing plots into Adobe Premiere.

2.3. *Hypothesized Results*

I expect the Sérsic indices for both the bulge and disk particles of M31 and the MW to generally increase with time as the merger comes to form a single elliptical galaxy. Relaxation over time through collisionless two-body interactions should drive this process of increasing n overall. I would also expect the change in the luminosity profiles/Sérsic indices to be greatest at or just after pericenters in the merger, where it seems that the most dramatic changes in the galaxies' structures occur. It is possible that some Sérsic indices do actually lower, however, possibly due to something like initially-centralized bulge particles being redistributed to outer parts of the galaxy. In this case, it may be more informative to also fit Sérsic profiles to the galaxies as a whole so as to account for the net radial migration of bulge *and* disk stars taken together.

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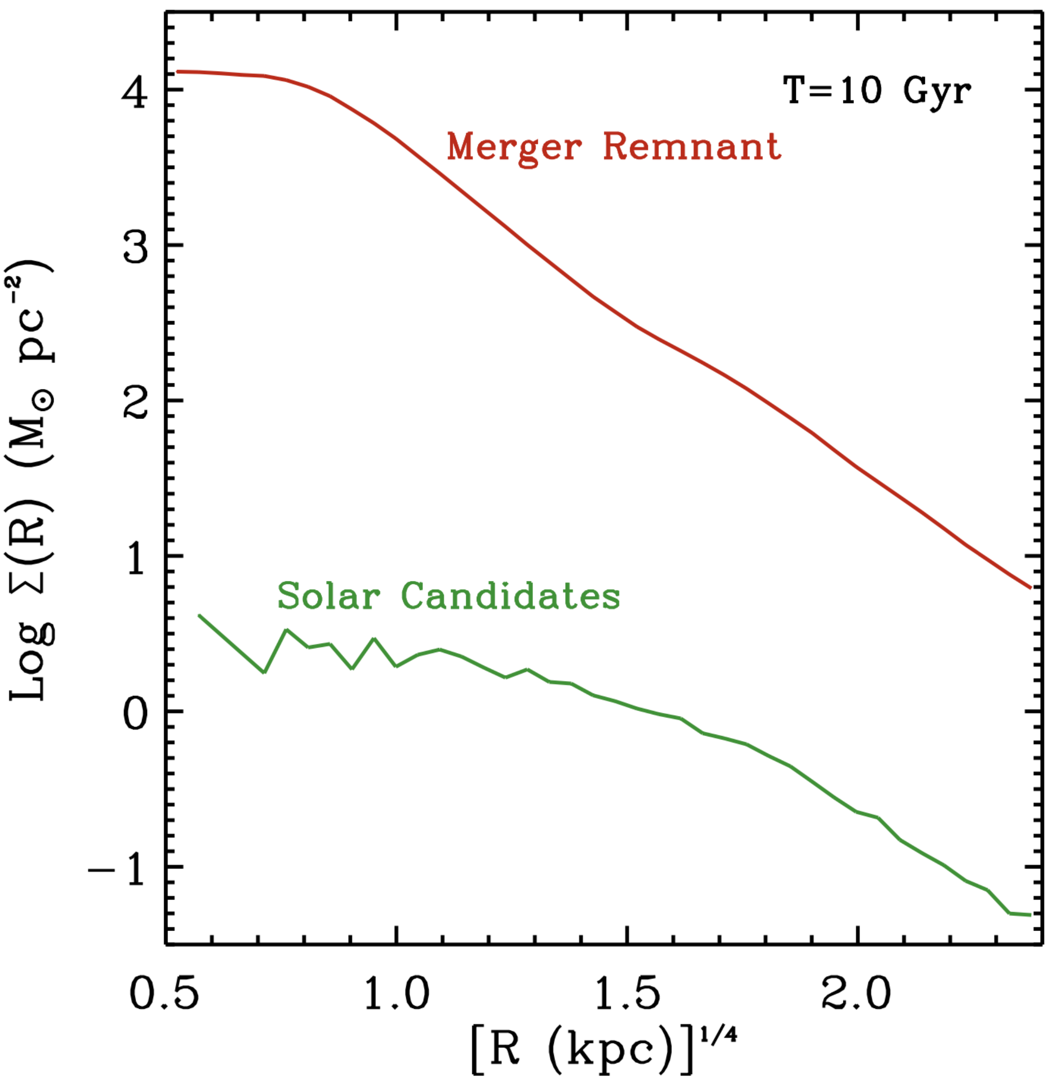

Figure 1. Figure 7 from van der Marel et al. (2012a), reproduced without permission. Here we see a surface mass density profile for the remnant and its solar candidates specifically plotted against the radius from the galactic center to the power of 1/4, with a semi-log plot. Surface mass density Σ can be converted to intensity I by assuming a mass-to-light ratio. The straight lines past $\sim$1 kpc indicate accordance with a de Vaucouleurs, $n = 4$ Sérsic profile.

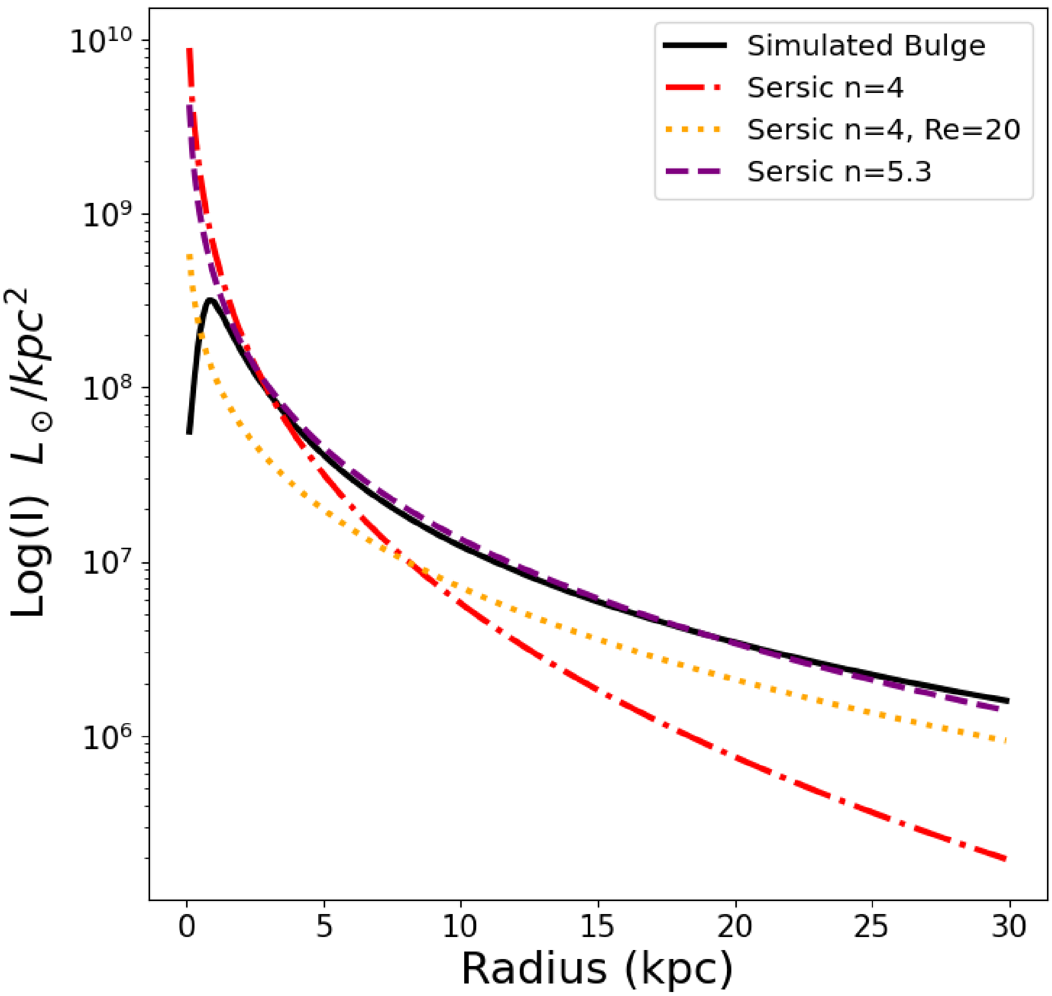

Figure 2. Plot from Lab 6 showing Sérsic profiles fit to the simulated bulge of M31 at the snapshot for $t = 0$ (the present epoch), with a semi-log plot of Intensity I versus distance from the M31 galactic center. Here we see how the effective radius (half-light radius) R_e affects the form of Sérsic profiles.