The Formation of S0-Type Galaxies as the Product of Major Mergers

Carl Ingebretsen,[1]*
[1] University of Arizona

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ABSTRACT
In this project, the formation of S0-type galaxies was investigated. The formation of S0 galaxies is still not well understood. In about 3 Gyr the Milky Way and the Andromeda galaxy will merge; this will be the major merger of two similar mass galaxies. It may be possible that the remnant of this merger could be an S0-type galaxy. The merger remnant was found to have some residual rotation. In addition, it was best fit by a Sersic profile with a disk and bulge component. The rotation and contribution to the light profile by a disk indicate the merger remnant is possibly an S0-type galaxy.

Key words: Local Group – Spiral Galaxy – Galaxy Merger – Merger Remnant – Sersic Profiles

1 INTRODUCTION

Lenticular galaxies (S0-type) are an unusual class of galaxies that incorporate structures of both spiral and elliptical galaxies. A spiral galaxy has a small bulge or bar in the center that is surrounded by arms rich in gas and dust, and with active star formation. An elliptical in contrast has a velocity dispersion-supported structure of stars with little cool gas or dust and no visible finer structure. A Lenticular galaxy has a large elliptical-like bulge in the center but is surrounded by a gas disk. This project aims to determine if the collision of two major spiral galaxies like the Milky Way and M31 can result in an S0-type galaxy.

A galaxy is defined to be a collection of stars, gas, and dust that are gravitationally bound together in such a way that gravity from the observed mass is not enough to keep the system bound (Willman & Strader 2012). This definition inherently includes dark matter as part of it since dark matter must be invoked to explain why the system is still bound. It is clear from the study of galaxies that dark matter is usually the dominant component of the mass thus its role in the system is undeniable. A galaxy merger is when two or more galaxies combine to form one larger galaxy.

Because a lenticular galaxy morphologically appears to be an intermediate between spirals and elliptical galaxies and elliptical galaxies are thought to form as the result of mergers of spiral galaxies, perhaps the lenticular galaxy is an intermediate stage in time after the spirals have merged but before they form a fully elliptical galaxy (Cox et al. 2006). Elliptical galaxies have little to no cool gas, suggesting that the gas ring of a lenticular galaxy could be left over cool gas of the spirals that hasn't been heated and ionized yet. The exact formation of elliptical galaxies through mergers is still not well understood. A spiral galaxy has considerable angular momentum while ellipticals generally due not and are dispersion supported(Cox et al. 2006). How the merger product evolves from being rotationally supported to dispersion supported is of interest. An S0-type galaxy's light profile can be described using a Sersic profile of about n=1.0 for the bulge

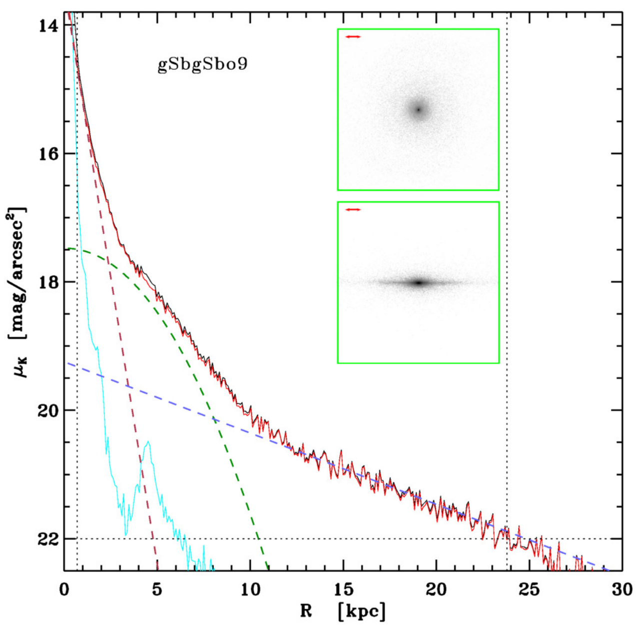

Figure 1. Image of the light profile of a simulated S0 type galaxy. It shows how the intensity of light for the lenticular galaxy depends on the radius from the center. Querejeta et al 2015

area(Querejeta, M. et al. 2015a). A Sersic profile is a function that describes the intensity of a galaxy as a function of the radial distance from the center. The light profiles of the bulge and disk can be fitted separately as seen in a figure provided by Querejeta et al (Querejeta, M. et al. 2015a). From observational evidence, one formation mechanism for S0 galaxies is ram-pressure stripping in galaxy clusters (Querejeta, M. et al. 2015a). However, there are many S0 galaxies observed outside the confines of clusters, indicating that the ram-pressure stripping can't be the only formation mechanism and hence indicating mergers may be able to result in S0 galaxies.

In this project, we intend to answer the question if a lenticular

* E-mail: carljingebretsen@arizona.edu

galaxy can be the result of a major merger between spiral galaxies. Currently, the full origin of Lenticular galaxies is not well known. From observations in galaxy surveys, it is known S0-type galaxies are present inside and outside galaxy clusters. Thus their formation is not tied only to galaxy clusters(van den Bergh 2009) There may be more than one formation pathway to form S0 galaxies. Currently, a number of research teams are studying the formation of S0-type galaxies using numerical simulations(Querejeta, M. et al. 2015b). Simulations are about the only way this is possible because one needs to see the entire merger process.

2 THIS PROJECT

This research project intends to explore if the merger remnant of the Milky Way and Andromeda galaxies could be an S0-type galaxy. The origin of the S0 galaxies is interesting since they are a galaxy with intermediate features between spirals and ellipticals. In connection with this question, I will also explore if the remnant of the merger is a slow or fast rotator. This could be a sign of an S0-type galaxy. If there is significant rotation in the merger remnant, it could be a sign that it is S0-type since an elliptical galaxy would not have significant net rotation.

A lead research question this study aims to address is if the S0-type galaxies could be the result of a major merger outside an environment of a galaxy cluster. One hypothesis for the lenticular galaxy formation is that they could be spirals whose gas was ram-pressure striped as they passed through a cluster. However lenticular galaxies are also observed far from clusters as well. Using the merger of the Milky Way and Andromeda galaxies as an example of a major merger between spiral galaxies, the remnant will be probed to determine if it is of type S0.

This study addresses the open question of lenticular galaxy formation outside galaxy cluster environments. Since the final product of a major merger is expected to be an elliptical galaxy, this study may show that a lenticular is merely an intermediate stage in the merger process as the merger remnant evolves into a true elliptical galaxy. However, the possibility of a lenticular galaxy evolving into an elliptical will not be answered since this would rely on a study of how the gas in the disk is heated up and/or dissipates.

3 METHODOLOGY

In this project, the merger between the Milky Way and the Andromeda Galaxy is explored using N-body simulations. The N-body simulations used were created by van der Marel et. al. van der Marel et al. (2012b,a) Of the Local Group galaxies in only the Milky Way, M31 and M33 are present in the simulation. Each galaxy is divided into three components, disk stars, bulge stars, and dark matter. The gravitational forces between each particle of mass are calculated according to Newton's theory of gravity. Then, due to the acceleration of gravity, the positions and velocities of each particle are updated. In the simulation, this process is run for 800 Myrs of simulation time.

The goal of this project was to determine if the merger remnant of the Milky Way and Andromeda would be a lenticular galaxy. In order to do this Sersic profiles were fit to merger remnant. For the sake of simplicity, the mass-to-light ratio was taken as one. Then a combination of Sersic profiles of different indices was fit to the remnant. From this fitted profile it will be examined to see if there was a distinct contribution from a disk and bulge. As a sanity check, the rotational velocity as a function of the radius was plotted. If appreciable rotation is observed then this indicates that there may be a rotating disk.

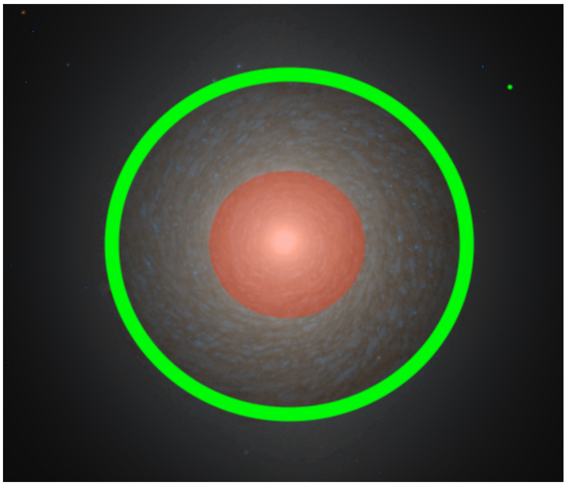

Figure 2. This is an image of an S0 galaxy with color overlays indicating the bulge and disk components. A Sersic profile was fitted to both components to determine if it is a lenticular galaxy.

The main task of the code that was written was to fit Sersic profiles to the merger remnant of the Milky Way and Andromeda. The mass-to-light ratio was taken to be unity to simplify the project. The method used to fit the profiles relied on the fact that disks and elliptical bulges have different profile functions. The profile of a disk and bulge profile were fit and if the contribution from the disk was negligible then the remnant is likely elliptical and not lenticular. The equation for a Sersic profile from the in-class slides is:

$$I(r) = I_0 e^{-(r/h)^{1/n}}, \tag{1}$$

where I is the intensity, I_0 is the central brightness, r is the radius, h is the scale length, and n is the index. For an elliptical galaxy, the index is 4 and for a spiral disk, the index is 1. For an elliptical galaxy this becomes:

$$I(r) = I_e e^{-7.67[(r/R_e)^{1/n}-1]}, \tag{2}$$

where I_e is the effective central brightness and R_e is the half light radius. For a spiral galaxy, the Sersic profile is:

$$I(r) = I_0 e^{-(r/h)} + I_e e^{-7.67[(r/R_e)^{1/4}-1]} \tag{3}$$

These profiles were fit to see if the galaxy has both a bulge and a disk.

The first plot made by this project was a graph of intensity vs radius. This graph will show the intensity vs radius for the galaxy from the data and the fitted Sersic profiles. Since a scipy fitting function was used, the profile would match the data very closely. The second plot was of velocity as a function of radius. This will be a sanity check to see if there is an appreciable rotation in the merger remnant.

Since a lenticular galaxy is a fairly rare type of galaxy it would be surprising if the remnant is actually a lenticular galaxy. It is likely that the remnant will be best described by a single Sersic profile of an index of about four. This would mean that the remnant is an elliptical galaxy. However, if the result is of type S0 there will be a contribution to the light profile from a Sersic profile of index 1.

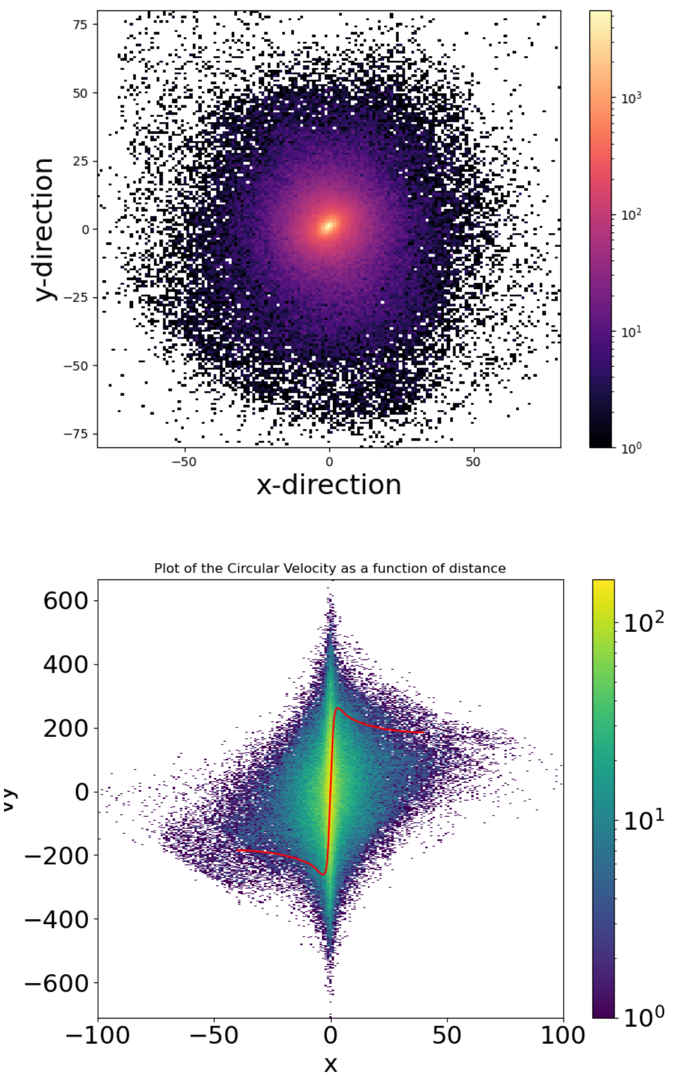

Figure 3. In the first panel of this figure an image of the remnant galaxy is displayed. This is a view looking down along the axis of rotation which is the angular momentum vector of the galaxy. The color corresponds to the density of stars in the location. The galaxy appears to be elliptical in this view. In the lower panel there is an image of the velocity curve of the galaxy. Along the x-direction is plotted the distance from the center of the galaxy. On the y-axis is the magnitude of the y-velocity. It is plain from this figure that there is some rotation in the remnant galaxy disk stars.

4 RESULTS

In the first panel of figure 3 an image of the remnant galaxy is displayed. This is a view looking down along the axis of rotation which is the angular momentum vector of the galaxy. The color corresponds to the density of stars in the location. The galaxy appears to be elliptical in this view. the point of including this figure is to check that the galaxy looks reasonable not an irregular shape. In the lower panel, there is an image of the velocity curve of the galaxy. Along the x-direction is plotted the distance from the center of the galaxy. On the y-axis is the magnitude of the y-velocity. It is plain from this figure that there is some rotation in the remnant galaxy disk stars. This is good evidence that the galaxy may in fact be lenticular.

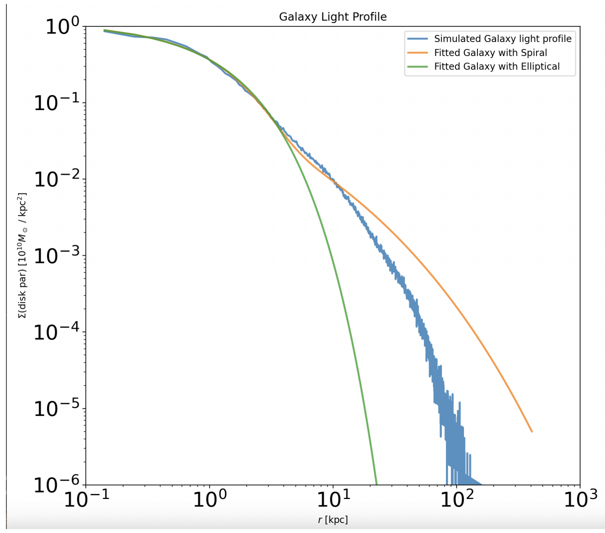

Figure 4. This figure depicts the fitted Sersic profile of the galaxy. The x-axis is the distance from the center of the galaxy in Mpc. The y-axis is the surface brightness of the galaxy assuming a mass-to-light ratio of 1. The fitted orange line is the combined profile of a disk and bulge fitted to the galaxy. The Sersic index found is 3.74, which is close to that of an elliptical but slightly lower than the canonical value of 4.

In figure 4, the fitted Sersic profile of the galaxy is displayed. The x-axis is the distance from the center of the galaxy in Mpc. The y-axis is the surface brightness of the galaxy assuming a mass-to-light ratio of 1. The fitted orange line is the combined profile of a disk and bulge fitted to the galaxy. The Sersic index found is 3.74, which is close to that of an elliptical but slightly lower than the canonical value of 4. This would seem to indicate that there may be a spiral component contributing to the light curve.

5 DISCUSSION

The fact that the merger remnant in figure 3 apparently shows rotation is support that the remnant is a lenticular galaxy. This would correspond to existing rotation curves of lenticular galaxies from the literature (cite it). However, it may be the case the remnant is in fact elliptical but has some residual rotation that will be dampened out by random gravitational interactions between the stars as time goes on. Thus this plot alone is not conclusive in identifying if the galaxy is elliptical or lenticular.

The uncertainties in the rotation curve can be estimated by the thickness of the wings. One could fit a line going through this distribution and the variances from the fit could be interpreted as the uncertainties. Since the distribution is thick there is considerable spread in the velocity values.

The Sersic profile fit from figure 4 is not very ideal. At large distances from the center, the combined bulge and disk do not fit well. However, at small radii, the fit works well. What is evident from the figure is that the spiral galaxy Sersic profile is a much better fit than the elliptical galaxy. This would be an indication that there is a contribution to the light profile of the merger remnant from a disk. This result is supportive of the the Milky Way and Andromeda merger creating a lenticular galaxy.

Since the light profile is fit with a curve fitting function, the function also returns an error value for the fit. This value is the one-sigma error on the seresic index. Since the curves are well fitted, the errors calculated are small. On the spiral sersic profile fit the one-sigma error on the index was 0.057. On the elliptical sersic profile fit the one-sigma error on the index was 0.025.

6 CONCLUSION

The formation of lenticular galaxies is still not well understood. They are possibly the merger remnants of major mergers between spiral galaxies. They are unusual since they are very similar to elliptical galaxies but with a ring of dust that lacks spiral arms. This project explored the possibility that the remnant of the Milky Way and Andromeda merger could be a type S0 galaxy.

From the simulation of the merger remnant the disk particle of the last snapshot was analyzed. From the picture of the galaxy remnant, the remnant appears to be elliptical in morphology. This is expected since a lenticular galaxy is very similar to an elliptical. From the plot of the velocity as a function of the distance from the center, there appears to be some coherent rotation. This supports the hypothesis the remnant is a lenticular galaxy.

The main result of the project was fitting a Sersic profile to the light profile of the galaxy. This analysis assumed the mass-to-light ratio was unity. The result is less than satisfactory. The fit is accurate at small distances from the center and not well fit at large radii. Since a profile with a disk is a better fit than an elliptical profile, It is suggestive that the galaxy has a disk component. This in turn suggests the merger remnant of the Milky Way and Andromeda could be a type S0 galaxy.

A possible avenue of future study is to analyze more than the final snapshot. It may be the case the galaxy has not settled down to its final state yet. Another possibility to study the formation of S0 galaxies would be to run new simulations with galaxies of different mass ratios and relative speeds.

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This research made use of NumPy (Harris et al. 2020) This research made use of matplotlib, a Python library for publication-quality graphics (Hunter 2007) This research made use of SciPy (Virtanen et al. 2020) This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2018, 2013)

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